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GE DOCUMENT NO. 64SD913

STUDY ON APPLICATION OF NUCLEAR ELECTRICAL POWER TO MANNED ORBITING SPACE STATIONS

FINAL SUMMARY REPORT

Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
21000 BROOKPARK ROAD
CLEVELAND, OHIO

7 SEPTEMBER 1964

GENERAL ELECTRIC

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7 SEPTEMBER 1964

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NOTICE

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LIST OF NOMENCLATURE

A consistent set of nomenclature is used in this report as follows:

- Reference SNAP-8 --------------------the entire SNAP-8 system currently being developed for unmanned applications.
- Electrical Generating System (EGS) or Nuclear Powerplant --the entirety of a nuclear power system including reactor, power conversion loops and controls.
- Power Conversion System (PCS) or Power Conversion Loops (PCL) -----the power conversion equipment or loops exclusive of the reactor and the reactor loop components.
- Pump/Motor Assembly (PMA) ----------a pump and its motor.

ACKNOWLEDGEMENT

Messrs. C. Johnson, D. Mason, and L. Maki of Atomics International considerately interrupted their schedules to prepare the Classified Appendices to the Second and Third Topical Reports. These appendices describe the SNAP-8 Reactor and its growth potential.

1. INTRODUCTION

A twelve month study on the application of nuclear-electric power to manned orbiting space stations has been completed. The program has been conducted by the Advanced Nuclear Systems Engineering component of the General Electric Company under NASA contract NAS3-4160, and has been directed by the Lewis Research Center.

The overall purposes of the study are:

- Evaluation of nuclear systems as the prime source of electric power for manned space stations and examination of questions relating to the feasibility of this application.
- Development of parametric data to aid the space station designer in the integration of the power supply with the station, and to aid the powerplant designer in adapting the plant to the space station application.
- Preparation of a preliminary powerplant design based upon the SNAP-8 reactor applied to a specific station.
- Provision of specifications to guide the development of SNAP nuclear power systems for maximum compatibility with the manned space station application.

The results obtained are detailed in five reports(1) and are summarized in this final report.

The results show that it will be possible to adapt nuclear systems that are presently under development to provide the high degree of reliability necessary for this manned mission. Initial system launch weights, including shielding, are comparable to those

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(1) "Study on Application of Nuclear Electric Power to Manned Orbiting Space Stations:

(a) Phase I, Feasibility Studies and Parametric Data", Document No. 63SD865, 20 Dec. 1963.

(b) Phase II, Station/Powerplant Integration Studies," Document No. 64SD647, 5 June 1964.

(c) SNAP-8 Reactor Support Data," Appendix A to (b) above, Classified CRD, Document No. 64SD767, 5 June 1964.

(d) Phase III, SNAP-8 Evaluation and Development Program Recommendations," Document No. 64SD914, 7 September 1964.

(e) SNAP-8 Reactor Growth Potential," Appendix A to (d) above, Classified SRD, Document No. 64SD945, 7 September 1964.

of solar photo-voltaic systems when the fuel required to compensate for solar array drag and to maintain orientation is considered. The nuclear hazard to the general public in this application is lower than that presently accepted in central station power and marine propulsion applications of nuclear power.

Fully surrounding, 4 π reactor shields are examined. An arrangement which allows for unrestricted access to the power conversion system and retention of greater than 80% of the shield at plant replacement are major design features. The techniques for in-space replacement and for old powerplant disposal are examined. The 35 KWe SNAP-8 system under current development and its reliability goals and operational requirements are described and compared to the requirements of a manned space station. Variations in the system design, employing the same technology and similar components, are presented to indicate how the SNAP-8 reactor and components can be used to fulfill these requirements.

At pertinent points in this summary, references are given to the three topical reports that describe in detail the results of the study.*

* These references are in the text and, for example, are given as (III, Section 5.1), meaning the Third Topical Report, Section 5.1.

2. CONCEPTUAL DESIGN

This section presents the summarized conceptual design for a modified 35 KWe SNAP-8 Electrical Generating System for application with a manned, earth orbiting, space station. The design is obtained through optimum choice among the parametric studies reported in Topical Reports I, II, and III.

2.1 SPACE STATION DEFINITION (II, SECTION 3.1)

The nuclear system is applied to the large 3-spoke station currently being investigated at the NASA Manned Space Craft Center, Houston, Texas. The station, shown in Figure 2.1-1, is formed by three modules that are attached radially to the central hub, which includes the docking hanger, a centrifuge, and a zero-g laboratory. The three radial modules or spokes each contain six levels or compartments with the living areas and duty stations at the outer ends of the spokes. Access from one compartment level to another and between spokes is provided by elevators and ladders in the access tubes on the sides of each spoke. The station rotates at about 4 RPM. It will be launched by a single Saturn V and will be deployed to the configuration shown in Figure 2.1-1 after attaining orbit. The design parameters of the station are summarized in Table 2.1-1.

2.2 POWER CYCLE (II, SECTION 6.1)

To provide for increased reliability and additional operational flexibility, component redundancy is included in the reference SNAP-8 power cycle. Alternate methods of including redundancy were examined and the results indicate that the greatest reliability improvement is obtained with independent redundant loops rather than redundant components within loops. The modified SNAP-8 cycle is shown in Figure 2.2-1. System modifications include a second primary NaK PMA, a second mercury and heat rejection loop, and a second coolant-lube loop, and additional instrumentation and controls.

The major system components are the same as those currently being developed in the SNAP-8 Program except for the boiler. Integration studies show that a modified boiler configuration is desirable to minimize shielding requirements. The modified boiler will contain two sets of parallel tubes and can be fabricated with the technology and techniques developed for the SNAP-8 boilers.

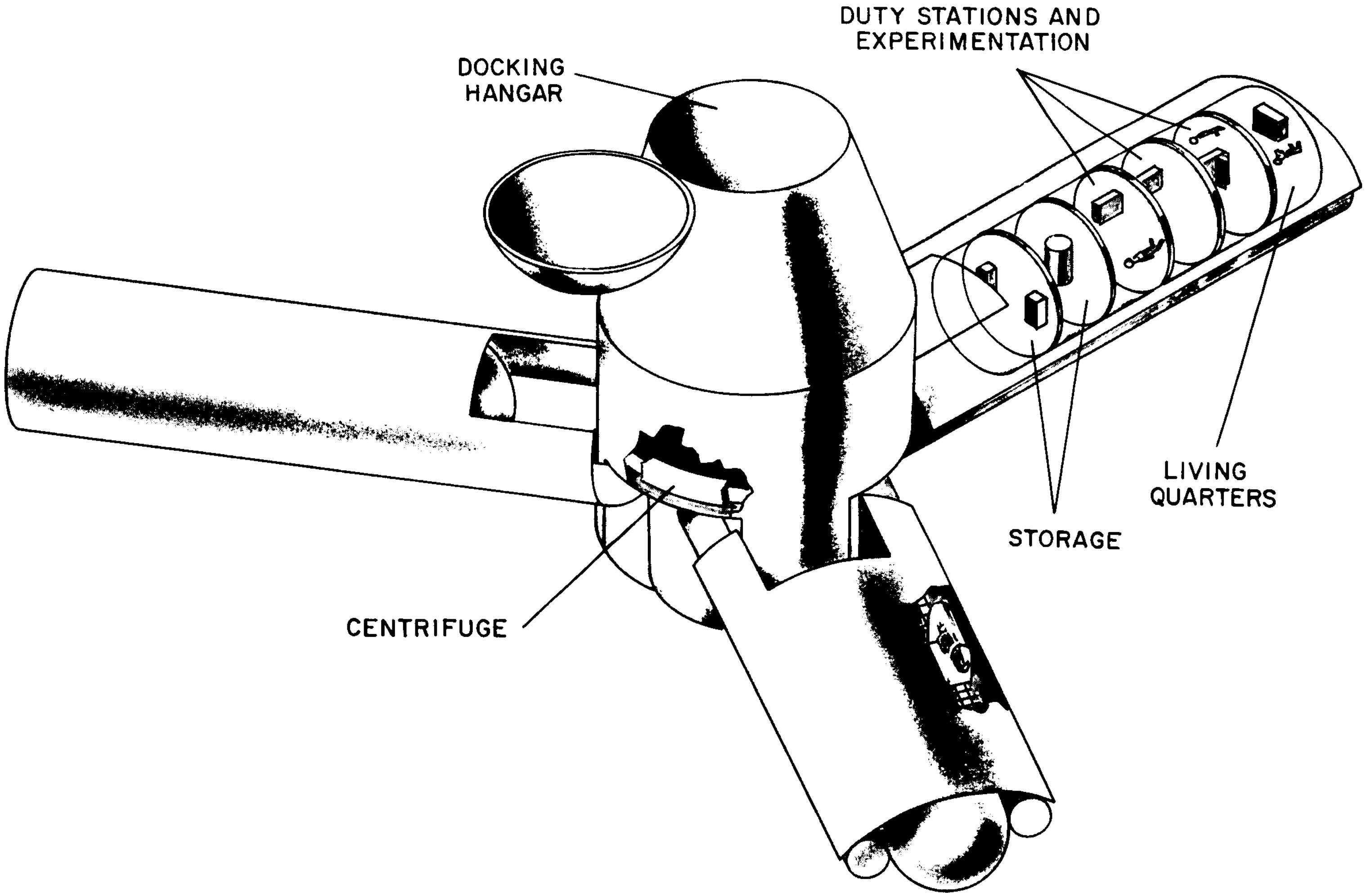


Figure 2.1-1. Reference Space Station Configuration

TABLE 2.1-1. SPACE STATION DESIGN PARAMETERS

Total Weight (Manned & Supplied)	250,000 lbs
Diameter (Deployed)	150 ft
Diameter of Spokes	15 ft
Diameter of Access Tubes	5 ft
Diameter of Hub	33 ft
Length of Spoke	~ 50 ft
Launch Vehicle	Two-Stage Saturn V
Orbit	260 Nautical Mile 29.5 Deg. Inclination
Mission Duration	5 Years
Launch Date	1968-1970
Crew Size	24 to 36

Design power can be generated by operating the power conversion loops (PCL) singly or in parallel. With a single PCL, the operating conditions are similar to those of the present system as shown in Figure 2.2-2. These cycle conditions are typical of those obtained when one set of components is inoperative due to failure or is held as standby spares. With two power conversion loops operating in parallel, various operating conditions may be obtained; however, cycle studies indicate that the conditions shown in Figure 2.2-3 are near optimum. The important differences between these and the reference cycle conditions are that:

1. Reactor outlet temperature is reduced from 1300 to 1270°F.
2. Reactor power is increased from 414 to 549 KWt.
3. Turbine inlet conditions are reduced from 1250°F, 265 psia to 1200°F, 200 psia.

This latter effect is important because there is a corresponding reduction of mercury boiling temperature from 1130°F to 1040°F. This is expected to reduce the corrosion rate in the boiler tubes by a factor of approximately 10 which should significantly increase boiler reliability.

2.3 SHIELDING (I, SECTION 3.2 AND II, SECTION 5.7)

2.3.1 CREW DOSE LIMITS (I, SECTION 3.2)

Sufficient shielding is provided to limit the total radiation dosage to the crew to 22 rem during a one-year tour of duty. This total consists of 16 rem (approximately 2 mrem/hr) while inside the station confines; 4 rem during extra-station operations, and 1 rem during each of two rendezvous operations. The station shielding is designed for unrestricted occupancy (i.e., 2 mrem/hour maximum) of the entire station with the reactor at 600 KWt for one year. This assumption is conservative since proper arrangement of equipment and designation of crew job assignments can allow higher dose rates for normally unmanned areas and for duty stations with limited exposure times. The shield design can effect significant weight savings by taking these factors into account.

2.3.2 SHIELD DESIGN PARAMETERS (I, SECTION 3.2 AND II, SECTION 5.7)

The shield design is for a spoke mounted powerplant with a separation distance of 50 feet between reactor and station, a closest approach distance of 50 feet at rendezvous, and a rendezvous vehicle deceleration rate of 0.5 ft/sec^2. These have significance as follows:

a. Powerplants may be integrated with the station in the two positions shown in Figure 2.3-1. A spoke-mounted powerplant is used in the conceptual design; however the shield design would be very similar for a hub-mounted system.

b. The choice of separation distance is a compromise affected by many factors and the distance of 50 feet is near optimum.

c. A 4π fully surrounding shield is provided to prevent the reactor from imposing operational restrictions on the station. The closest approach distance and deceleration rate define the worst approach path of the rendezvous vehicle and determine the shielding that must be provided to limit the rendezvous dose to 1 rem.

The shield is shown in Figure 2.3-2 and is composed of lithium hydride and tungsten. Lithium hydride is selected for the neutron shield because of its low density, high hydrogen content, and high (n, α) cross section. Tungsten in the form of Hevimet alloy (90W-6Ni-4Cu), is selected as the gamma-shield material because of its high efficiency attenuation of gamma rays and its relatively good structural characteristics.

Although heavy gamma shielding is normally placed as close to the reactor as possible to conserve weight, the secondary gamma production in the tungsten alloy (Hevimet)

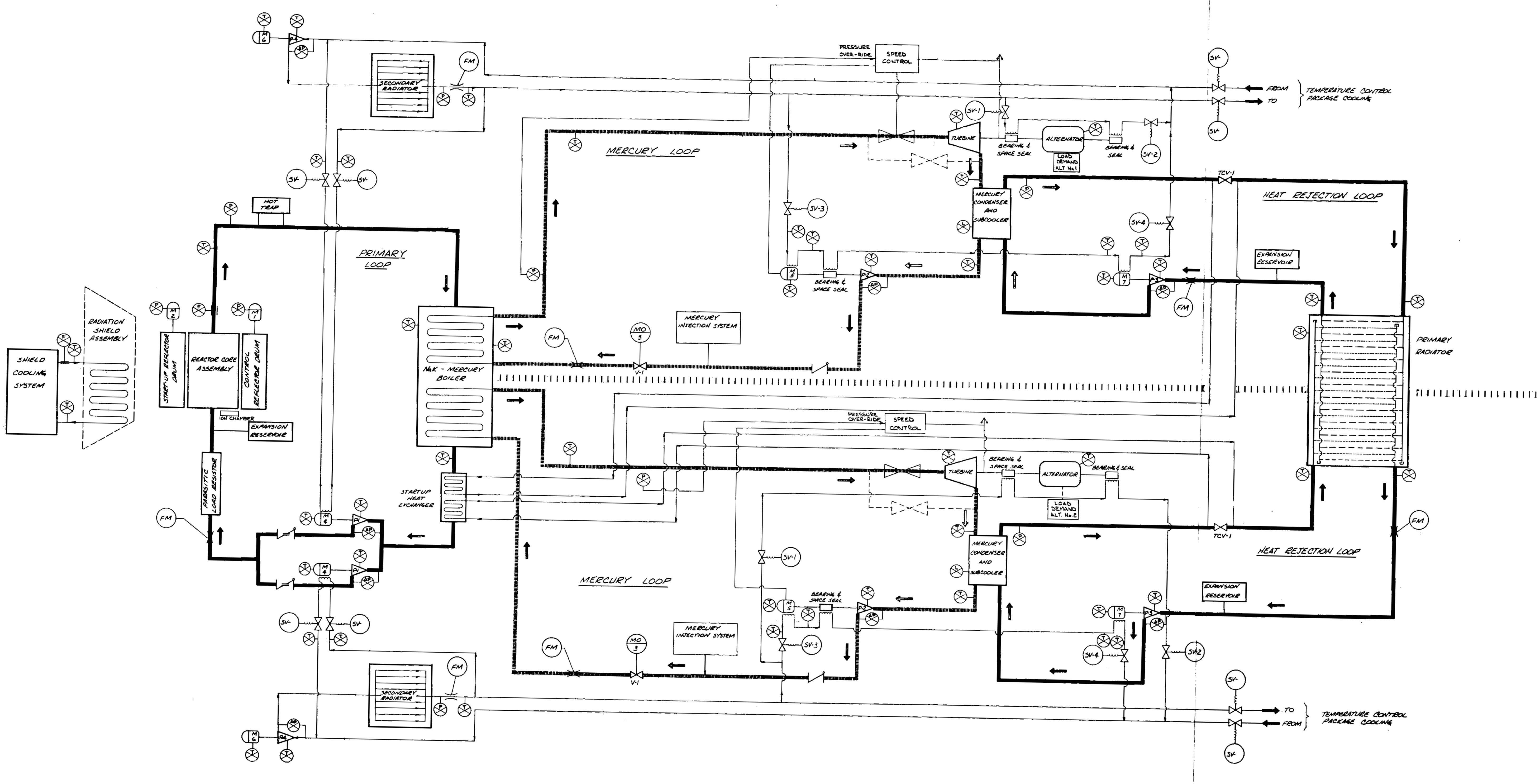
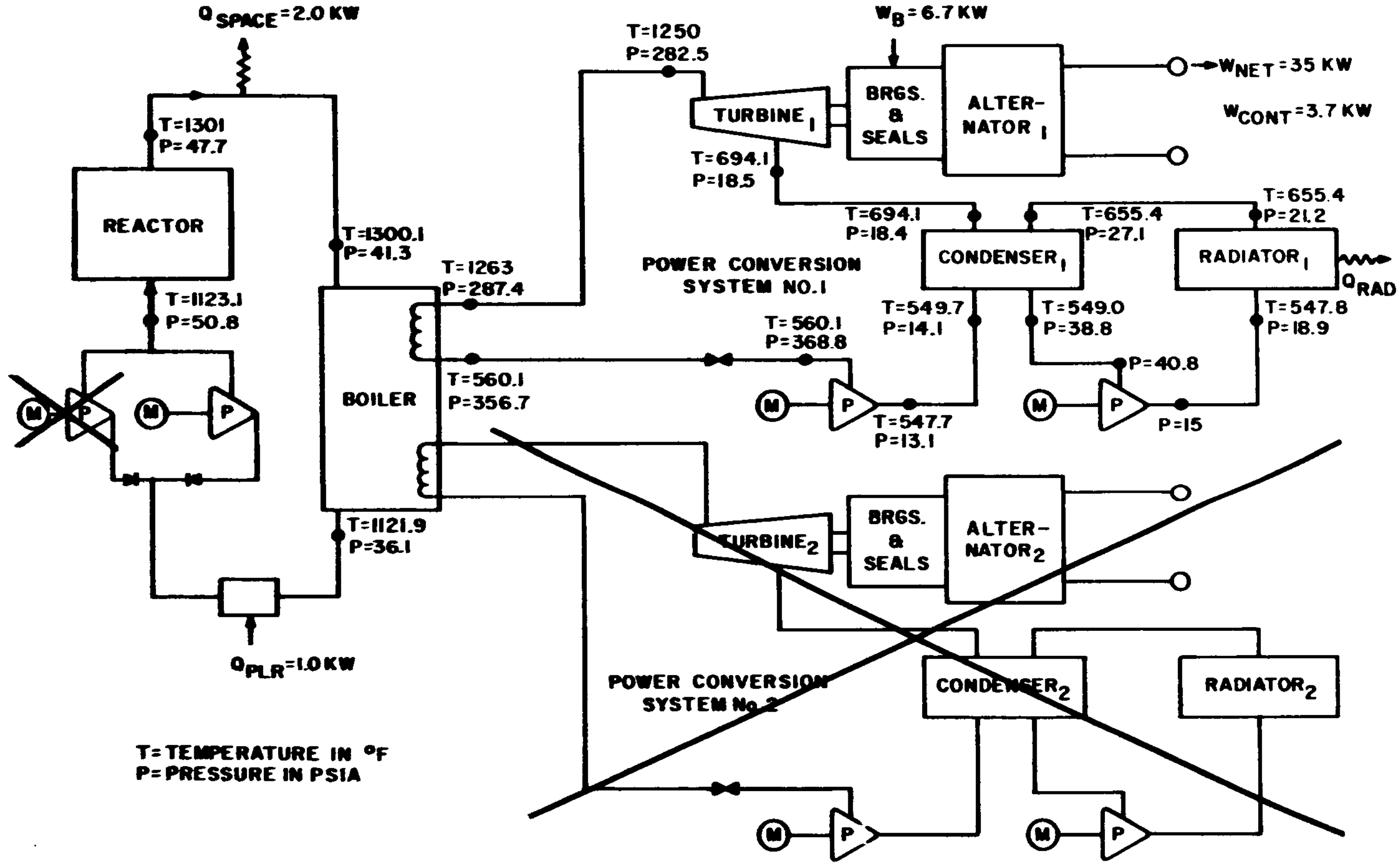


Figure 2.2-1. SNAP-8 Cycle with Redundant Components in Parallel Loops



REACTOR PUMPS INPUT = 1.8 KW
REACTOR NaK FLOW = 37721 LB/HR
$Q_{REACTOR}$ = 413.6 KW
$Q_{CONDENSER}$ = 353.5 KW
ALTERNATOR EFFICIENCY = 91.9%

MERCURY PUMP INPUT = 3.2 KW
MERCURY FLOW = 9747 LB/HR (EACH)
TURBINE EXIT QUALITY = 94.5 %
TURBINE EFFICIENCY = 62.1%
CYCLE EFFICIENCY = 8.45%
DEGREES OF SUBCOOLING = 121°F

RADIATOR PUMP INPUT = 3.9 KW
RADIATOR NaK FLOW = 54000 LB/HR
RADIATOR T_{eff} = 579.1°F
RADIATOR AREA = 950.4 FT^2
$Q_{RADIATOR}$ = 357.4 KW

Figure 2.2-2. Cycle Operating Conditions (Single Primary NaK PMA and Single PCS Loop at 35 KWe)

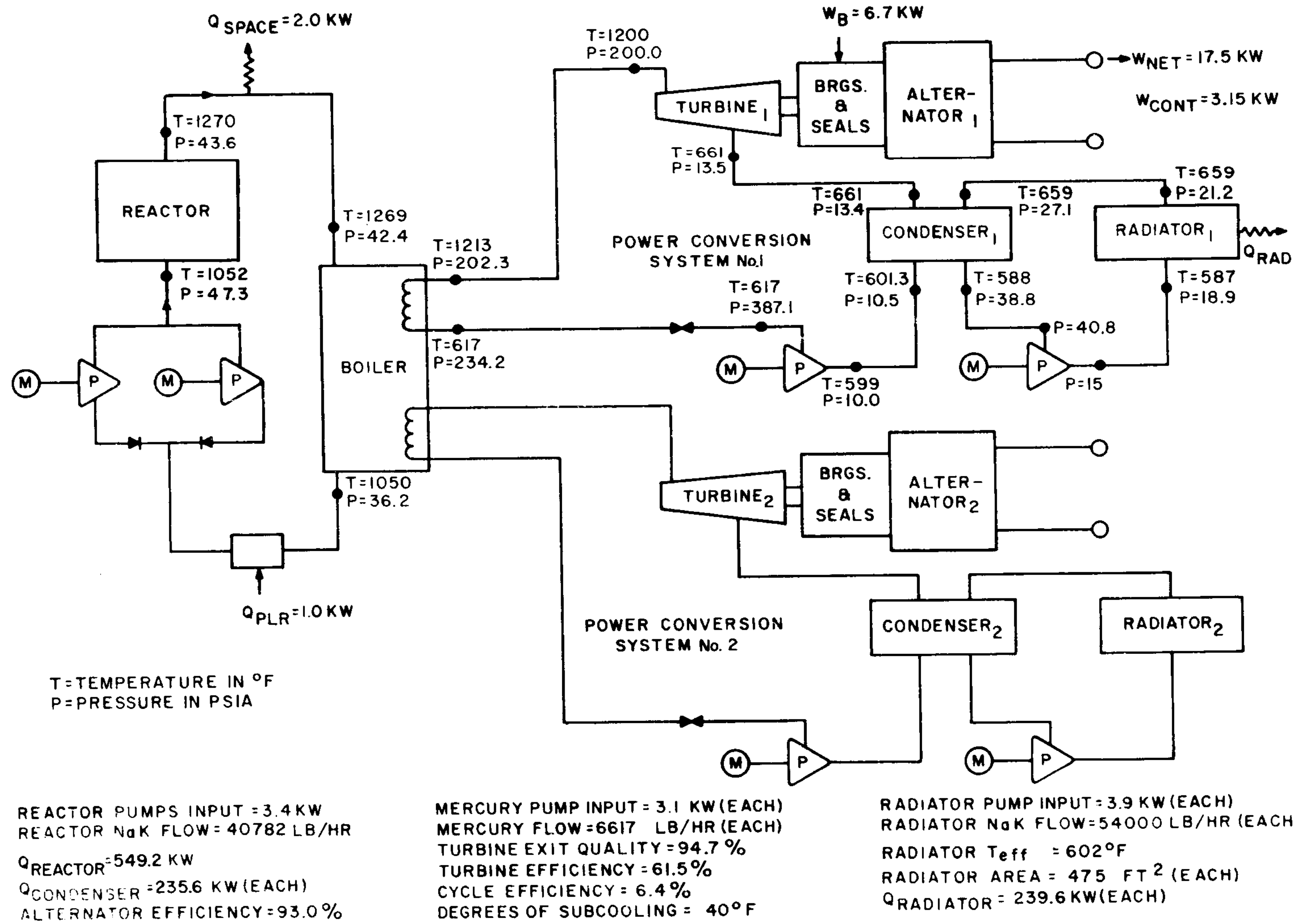
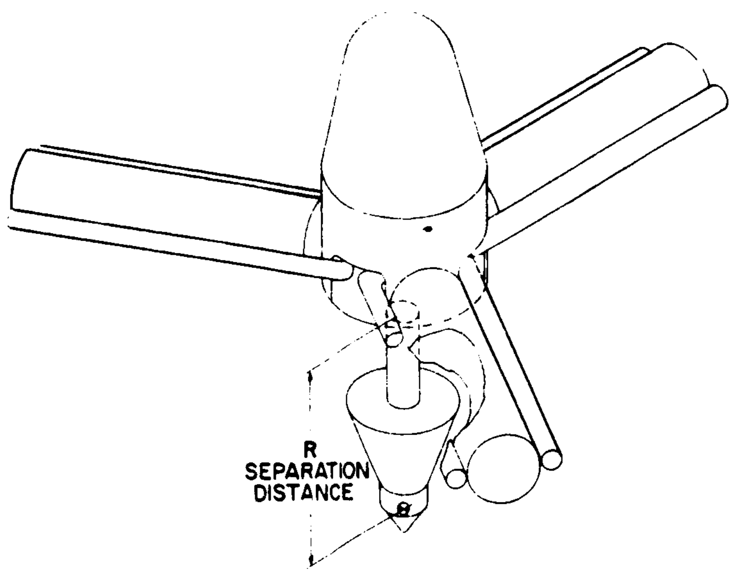
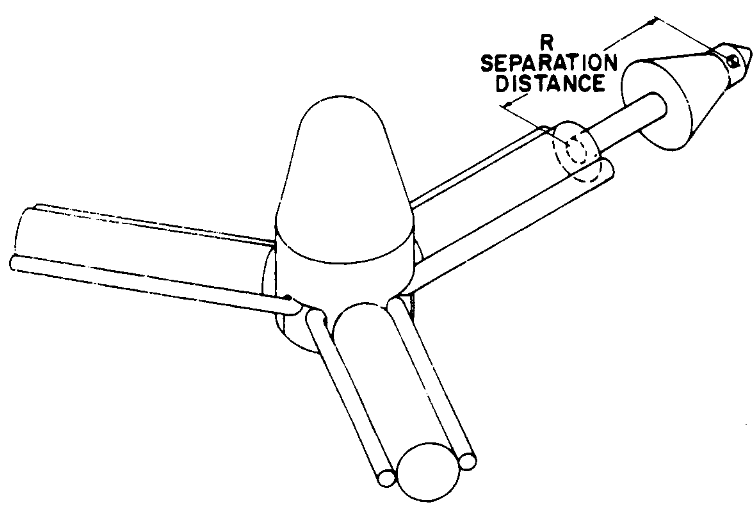


Figure 2.2-3. Cycle Operating Conditions (Parallel Primary NaK PMA's and PCS Loops at 35 KWe)



THREE SPOKE STATION, PLANT ATTACHED AT HUB



THREE SPOKE STATION, PLANT ATTACHED TO ONE SPOKE

Figure 2.3-1. Alternate Powerplant Locations

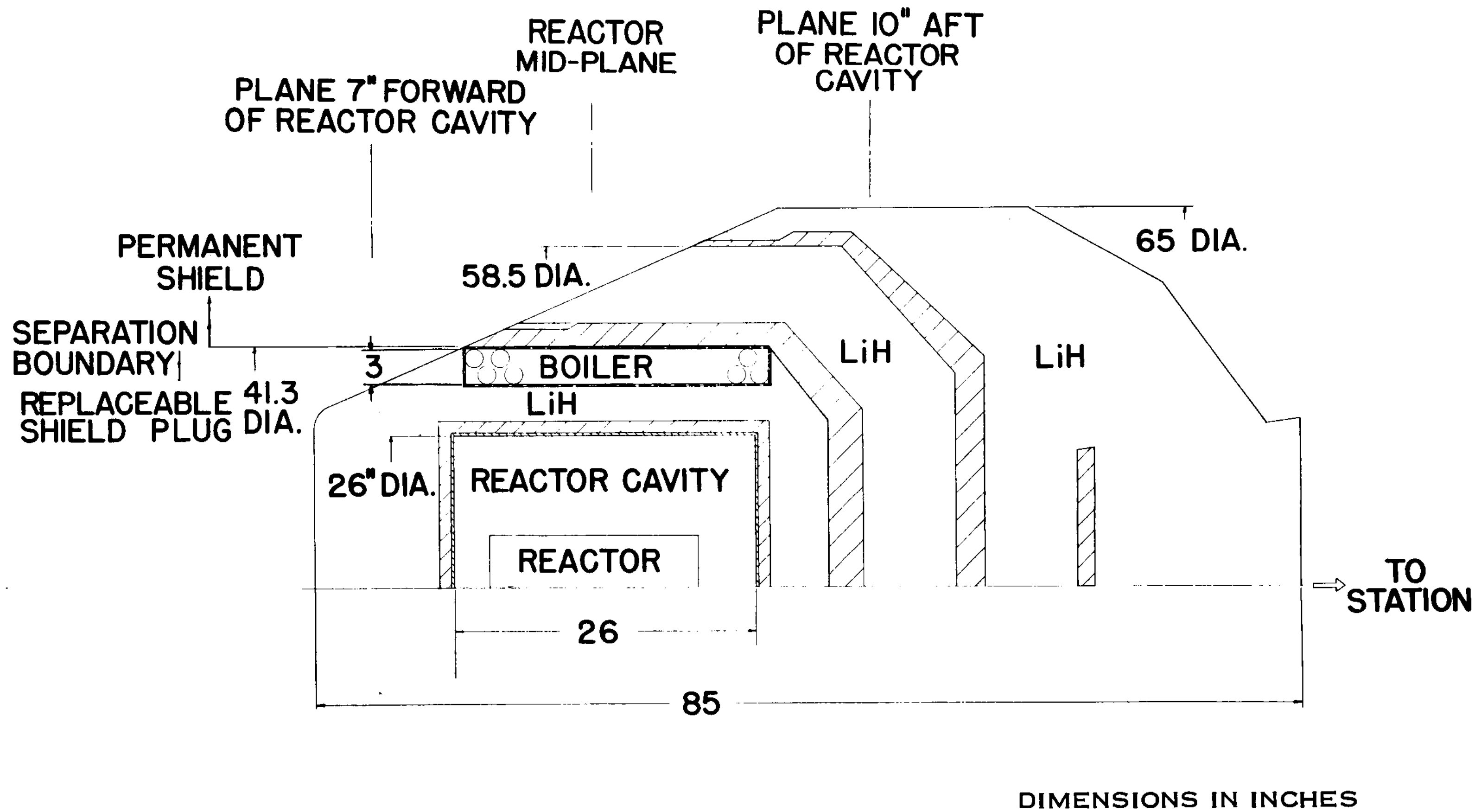


Figure 2.3-2. Shield Configuration

requires that alternate layers of Hevimet and lithium hydride be used to maintain neutron and gamma levels in proper balance. For minimum weight, neutron and gamma ray shield materials are spaced such that secondary and primary radiation are of equal importance, maintaining relatively thin layers of tungsten (2 inches or less).

The powerplant may have to be replaced one or more times over the lifetime of the space station and, the shield is designed in two sections: one section that will be replaced each time that the powerplant is replaced and a second section that will remain permanently attached to the station. The weight that is saved during replacement depends upon the location of the separation boundary between the replaceable and permanent shield sections.

In determining the placement of the separation boundary, the following is considered:

- It is desirable to keep the separation boundary as close to the reactor as possible since this moves the first layer of tungsten inward and reduces its weight. Also, the size and weight of the replacement shield section is reduced which reduces the weight of the replacement powerplants.
- Cooling coils or tubes are imbedded in the first several inches of shielding and since these tubes are connected into the powerplant, this portion of shield must be included in the replaceable shield section.
- The boiler is similarly connected into the powerplant and must be made a part of the replaceable shield section. The boiler is placed at the outer boundary of the shield plug because as the boundary is moved inward, the boiler is moved into a higher neutron flux and the mercury activation is increased.

The separation boundary illustrated in Figure 2.3-2, considers the above factors with the boundary placed as close to the reactor as possible consistent with the shield cooling limitations.

A secondary advantage of providing a two section shield is that the replaceable shield plug will receive a total gamma and neutron dose an order of magnitude greater than the dose in any other portion of the shield. If any radiation damage occurs, it will be greatest in the replaceable shield plug, and consequently, will be amenable to replacement.

The weight of the shield is given below:

Replaceable Shield Plug	3,100 lbs
Permanent Shield	17,100 lbs
Total Shield Weight	20,200 lbs

2.3.3 SHIELD COOLING (II, SECTION 5.7)

The SNAP-8 Reactor, as designed, radiates energy directly to space and the reflector and control drums are cooled by radiation to space. Enclosure of the reactor in a 4π shield requires active cooling to remove the heat generated therein and to cool the shield walls immediately surrounding the reactor which serve as a heat sink for the reflector and control elements. The total energy to be removed from the shield is conservatively assumed to be 10% of the total reactor power.

Several alternate cooling systems were evaluated and that shown in Figure 2.3-3 was chosen for the conceptual design. This system has the advantage that the shield cooling is accomplished by a bypass stream from the primary NaK loop and the shield heat is returned to the cycle allowing a reduction of reactor power. Also, no additional pumps are required.

A bypass stream of NaK is first subcooled to a temperature of 585°F by counter flow heat exchange with the subcooled mercury liquid that is entering the Hg boiler, then passed through the shield cooling coil where the temperature is increased to 970°F and returned to the suction of the NaK pump. The subcooling of the NaK can be accomplished in either a separate heat exchanger or a compartmented section of boiler. A heat exchanger with a UA of approximately 4000 BTU/hr°F is required. Utilizing an inlet temperature of 585°F to the shield cooling coil and with proper arrangement of the flow pattern in the shield, it is possible to hold the average surface temperature in the shield to a temperature of 650 to 700°F. With such a surface temperature, Atomics International indicates that the maximum reflector temperature can be held below 1325°F.

Shield cooling coils are included in the replaceable shield section. With two sets, of tubes, one set on the surface of the shield cavity surrounding the reactor and the other set imbedded 1.75 inches into the first layer of lithium hydride, maximum shield temperatures can be limited to 1000°F as shown in Figure 2.3-4.

The above two coolant streams enter the shield opposite the core midplane and flow toward the ends of the shield.

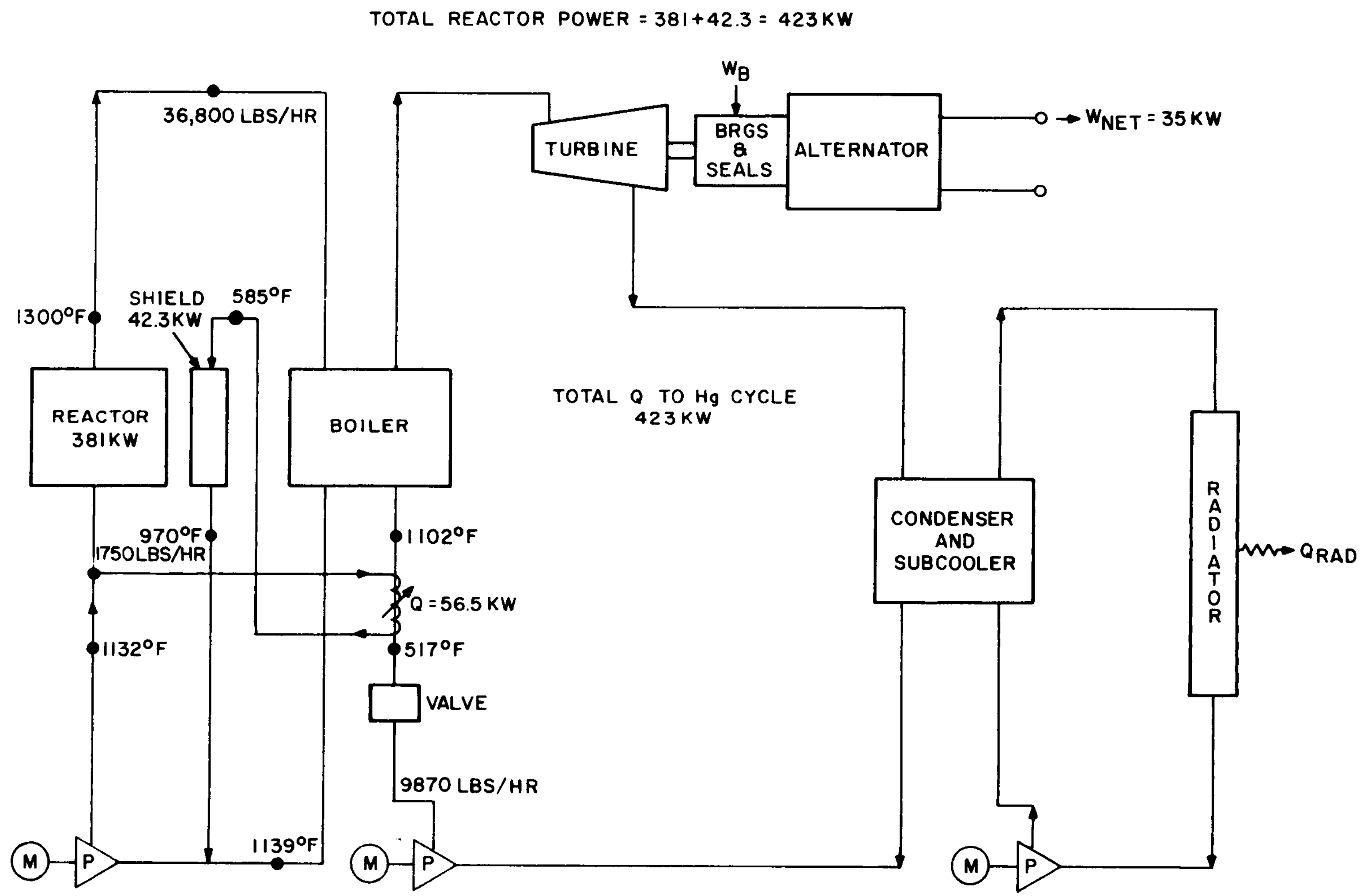


Figure 2.3-3. Shield Cooling System

NOTES

1. THE INDICATED GRADIENTS AT "A" AND "B" WOULD BE REDUCED BY APPROXIMATELY AN ORDER OF MAGNITUDE BY A TWO-DIMENSIONAL ANALYSIS.
2. TEMPERATURES INDICATED ARE IN °F.
3. COOLANT ENTERS AT REACTOR MIDPLANE AT 585°F AND EXITS ALONG THE CENTERLINE AT 975°F.
4. MAXIMUM "HOT SPOT" TEMPERATURE IN SHIELD BETWEEN INTERIOR TUBES IS 5.0°F ABOVE TUBE WALL TEMPERATURE.
5. MAXIMUM "HOT SPOT" TEMPERATURE IN SHIELD BETWEEN CAVITY LINER TUBES IS 0.4°F ABOVE TUBE WALL TEMPERATURE.
6. EMISSIVITY OF SHIELD AND SURROUNDING SURFACE IS 0.9.
7. REACTOR TEMPERATURE IS APPROXIMATELY 270°F ABOVE THE CYLINDRICAL LINER TEMPERATURE.

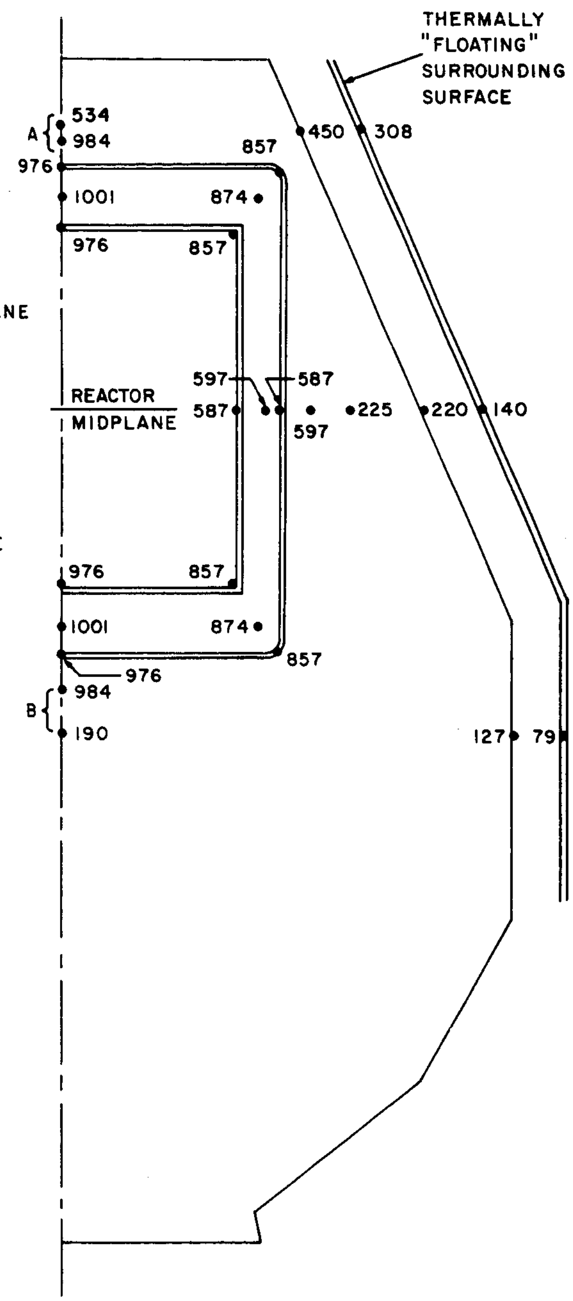


Figure 2.3-4. Approximate Shield Temperature Map

2.4 POWERPLANT ARRANGEMENT (II, Section 5.3)

The powerplant arrangement shown in Figure 2.4-1 was developed to meet the particular requirements of the three-spoke station. The more important factors governing this arrangement are discussed below.

2.4.1 EQUIPMENT MOUNTING

The radiator and PCS are located inboard of the reactor in order to allow access to the PCS components. To provide for connection of the reactor primary loop and the shield-cooling loop and for intact removal of the powerplant, the PCS and radiator are mounted on a cylindrical structure that is supported from, but not connected to, the boom. The cylindrical structure extends out over the permanent section of the shield and is attached to the replaceable shield and the primary loop components, including the reactor. In plant replacement, the entire powerplant consisting of reactor, PCS, radiator and replaceable shield will be propelled off from the support boom (in either one or two parts) leaving the support boom and the permanent shield section exposed. The separation boundary between the powerplant and the boom is shown in Figure 2.4-2.

2.4.2 EQUIPMENT ENVIRONMENT

For effective maintenance, the radiator structure is used to include the PCS in an enclosed environment. A seal is made at two points and a meteroid shield is included at the large end of the radiator as shown in Figure 2.4-1 to convert the area enclosed by the radiator into a pressure sealed compartment. The support boom is open within the area enclosed by the radiator; however, it is sealed between the end of the radiator and the space station. The support boom, therefore, serves the double purpose of supporting the powerplant and acting as a pressurized tube in allowing a man to move from the station to the powerplant without going outside of the station.

2.4.3 EQUIPMENT ARRANGEMENT

The equipment is also arranged to allow possible maintenance on the PCS. The NaK coolant is a significant source of secondary gamma radiation. At equilibrium and 600 kwt, the radiation dose rate at 20 feet from the primary loop is calculated to be 44 rem/hr. Thus the entire primary loop and all its components must also be shielded.

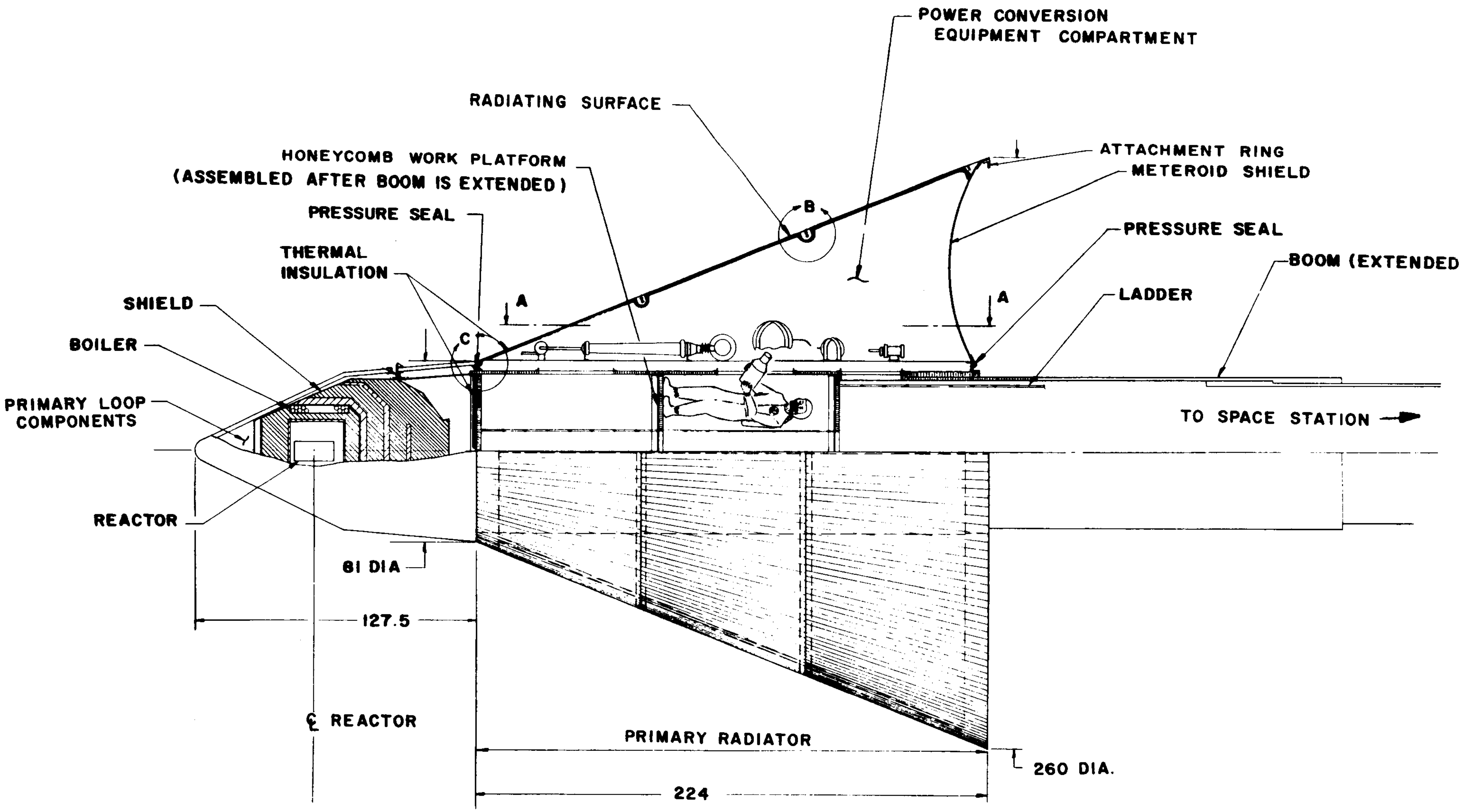
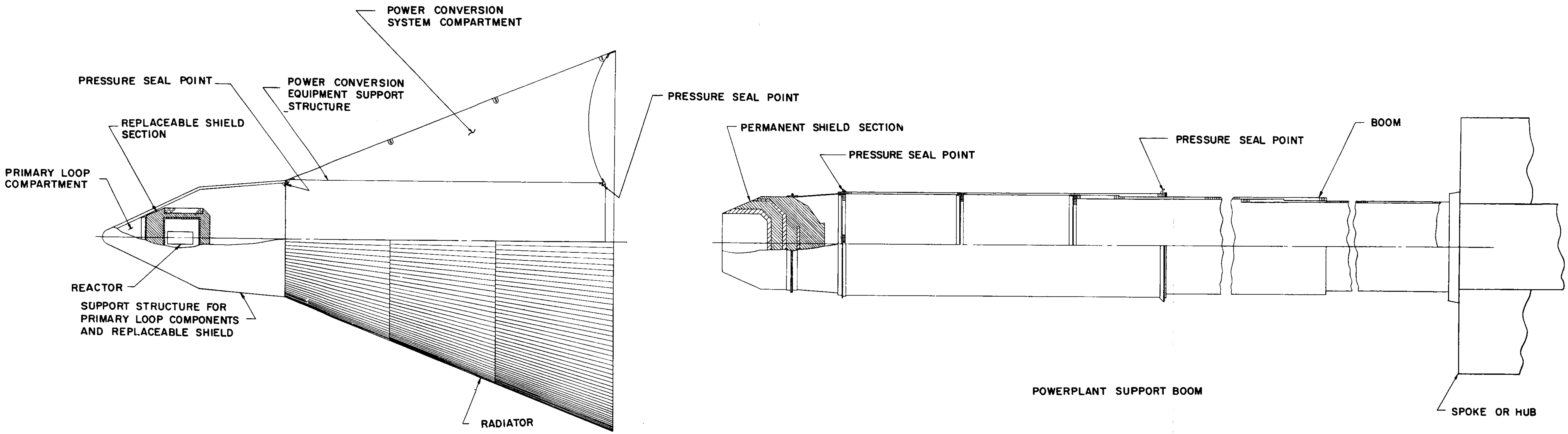


Figure 2.4-1. Powerplant Arrangement



POWERPLANT

POWERPLANT SUPPORT BOOM

Figure 2.4-2. Powerplant and Support Boom Separation

An examination of the shielding required around the primary loop shows that several thousand pounds of tungsten would be required even if the components were closely packaged. Consequently, the primary loop components are included in a compartment behind the reactor and the compartment is sized to accept the components in a close array. The annular boiler is included in the shield. The arrangement chosen, thus uses the reactor shield to also shield the primary loop components.

The turbine-alternator, mercury pump, and condenser are located closest to the small end of the radiator to minimize the length of the mercury lines connecting these components to the boiler. The remaining components are located as necessary within the powerplant compartment.

The radiation level at the PCS for a power level of 600 kwt is expected to be approximately 22 mrem/hr of which 13 mrem/hr will be direct reactor radiation and 9 mrem/hr will be secondary radiation from activated mercury.

2.5 RADIATORS (II, SECTION 6.4)

2.5.1 PRIMARY HEAT REJECTION LOOP RADIATOR

The primary NaK radiator, shown in Figure 2.4-1 is a conical frustrum, 224 inches high, having a base diameter of 260 inches and a top diameter of 81 inches. The principal material is aluminum and with the coolant tubes containing a stainless steel liner. The two loop-common fin system illustrated in Figure 2.4-3 is used to provide redundancy without increased radiator area. The two loop system provides a no-puncture probability of 0.999* for 10,000 hours at a matrix weight of 2100 pounds compared to a weight in excess of 3000 pounds for a single loop of the same reliability.

Radiator optimization studies show that a minimum weight and area radiator is obtained with NaK flow rates greater than the SNAP-8 reference design value of 36,700 lbs/hr. Optimum flow is 54,000 lb/hr which can be obtained with the present pump with decreased pressure drop in the radiator feeds, headers, and tubes. Radiator parameters are summarized for single and two loop operation in Table 2.5-1.

2.5.2 SECONDARY COOLANT-LUBE RADIATORS

Two radiators, each capable of rejecting 22.3 KW of heat, are provided for redundancy in accordance with the cycle shown in Figure 2.2-1. The radiators require an area of

*The reliability is that of at least one radiator loop surviving to 10,000 hours to provide full rejection capability.

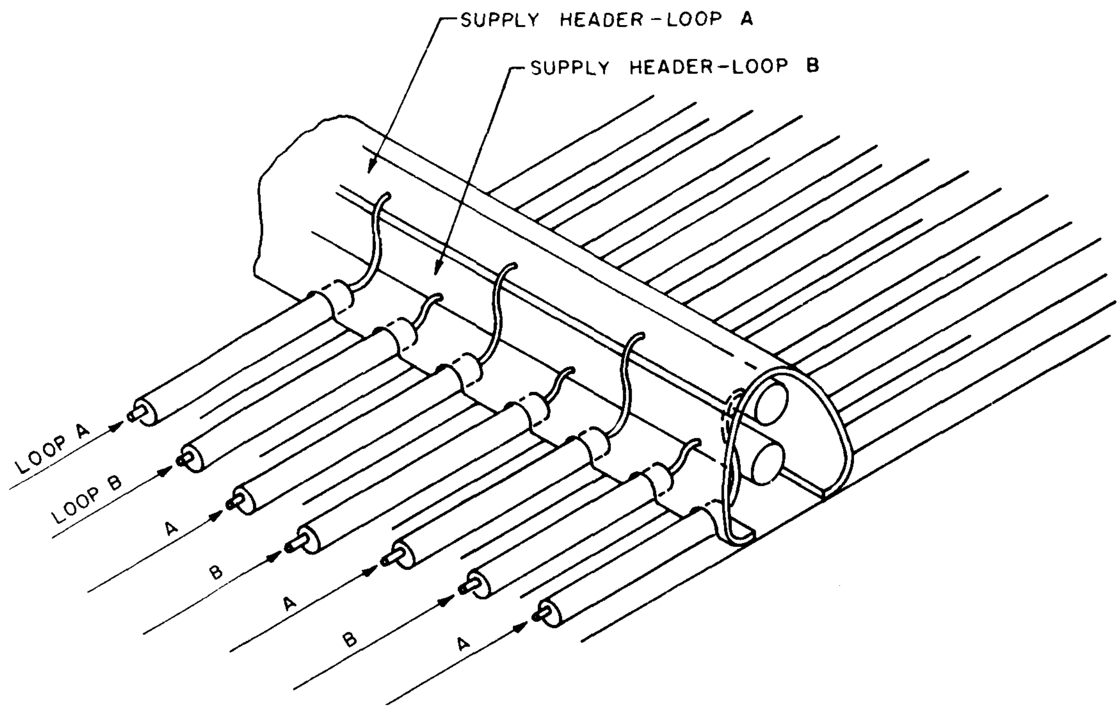


Figure 2.4-3. Radiator Panel with Two Fluid Loops

350 ft^2 each to allow for operation of the power conversion loops (PCL) in parallel. The common fin design cannot be used because each loop must reject approximately rated heat load when the power conversion loops are operated simultaneously. If the operation modes are restricted to allow the PCL's to operate singly only, then the common fin design can be utilized and the added area of one secondary radiator can be eliminated.

The radiators are 32 feet long by 11 feet wide. They are mounted near the end of the spoke which supports the nuclear powerplant. Each panel is divided into four bays, eight feet long. Feed and return lines run lengthwise down the center of the panel and the headers for each bay run crosswise. Secondary radiator parameters are summarized in Table 2.5-2. Weights are also included for a radiator designed for a 5-year life to show the small additional weight incurred in providing greater design life.

TABLE 2.5-1. SUMMARY OF PRIMARY NaK RADIATOR PARAMETERS

		TWO-LOOP OPERATION	SINGLE-LOOP OPERATION
Heat Rejected	KW	482	366
Area	ft^2	950	950
Coolant		NaK	NaK
Coolant Inlet Temp.	°F	667	667
Coolant Δ T	°F	73	110
Coolant Flow Rate	lbs/sec	30	15
Effective Av. Tube Spacing	IN	2.65	5.30
Total Weight Coolant	lbs	232	232
Total Weight Fins	lbs	865	865
Total Weight Tubes and Headers	lbs	964	964
Total Weight Feeds	lbs	256	256
Total Matrix Radiator Weight	lbs	2085	2085
Total Weight*	lbs	3505	3505

*Includes matrix plus header and feed armor, bulkhead, and support structure

2.6 INITIAL LAUNCH AND DEPLOYMENT (II, SECTION 5.2)

A constraining ground rule is that the entire Electrical Generating System (EGS) must be launched with the space station aboard the Saturn V booster. This requirement eliminates the need for the immediate rendezvous of an EGS with the station before station activation can occur.

The EGS is incorporated into the launch package so as to result in a minimum loss of station volume. Additionally, the lost volume is of lowest usefulness to the space station. This is accomplished by "nesting" the powerplant below the central hub and between the three folded spokes as shown in Figure 2.6-1.

TABLE 2.5-2. SUMMARY OF SECONDARY RADIATOR PARAMETERS

		10,000-HR LIFE	5-YEAR LIFE
Survival Probability (each loop)		0.98	0.98
Heat Rejected	KW	22.3	22.3
Area	ft^2	350	350
Coolant		ET-378	ET-378
Coolant Inlet Temp.	°F	246	246
Coolant Δ T	°F	26	26
Coolant Flow Rate	lbs/sec	2.08	2.08
Average Tube Spacing	IN	5.75	5.9
Total Weight Coolant	lbs	111	71
Total Weight Fins	lbs	218	264
Total Weight Tubes and Headers	lbs	165	250
Total Weight Feeds	lbs	94	46
Total Matrix Radiator Weight	lbs	477	560
Total Weight*	lbs	1520	1680
NOTE: Values shown are for one of two secondary radiators			

*Includes matrix plus header and feed armor, edge numbers stiffners, and support structure

The volume sculptured from the spokes is minimized by minimizing radiator volume and including the power conversion system within the radiator. The secondary radiators for the coolant-lube systems are attached to the station spokes. Deployment of the EGS is achieved through the series of steps shown on Figure 2.6-1.

This launch configuration is also suitable for a hub mounted powerplant. After the spokes are deployed, the powerplant is extended directly by its support boom to the necessary separation distance.

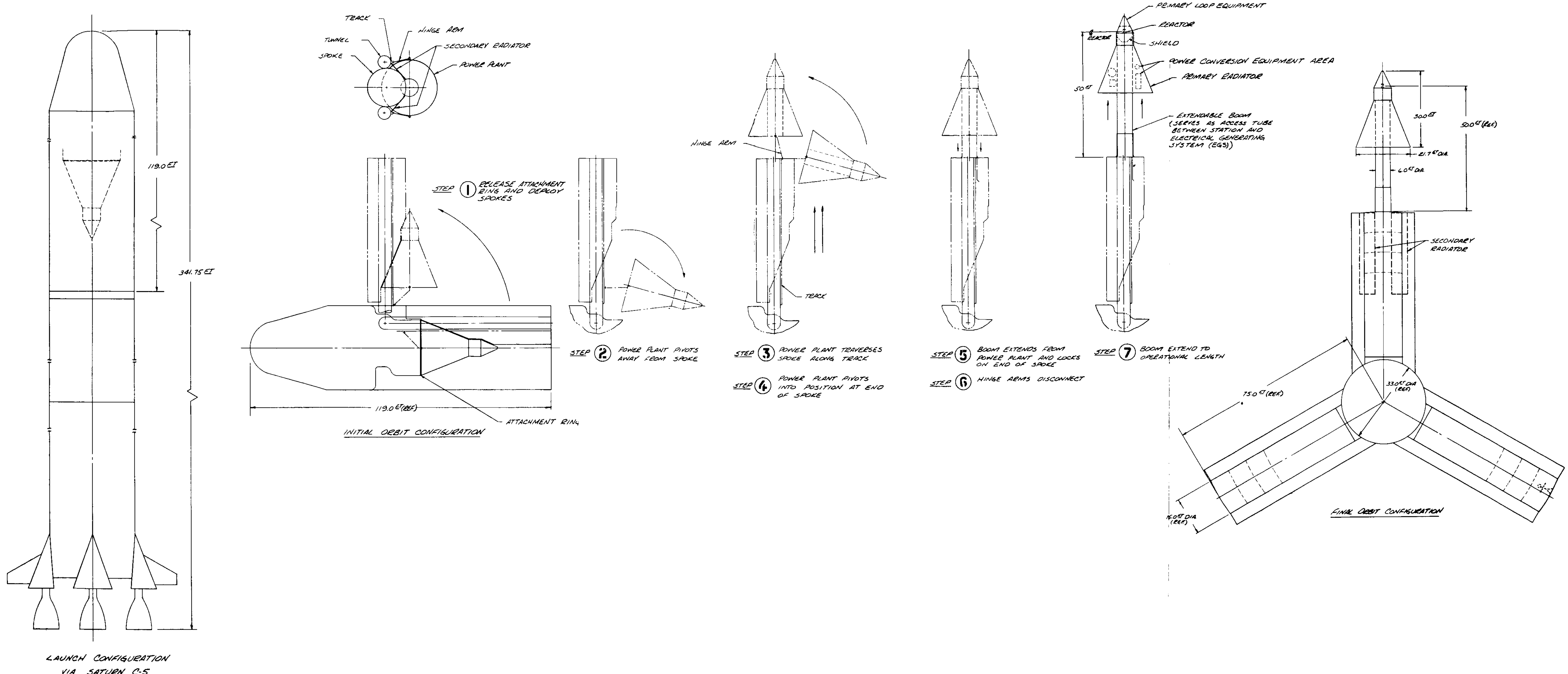


Figure 2.6-1. Reference Launch Configuration and Deployment Method (Spoke Mounted Powerplant)

2.7 STATION ROTATIONAL BALANCE (I, SECTION 3.4 AND II, SECTION 5.1)

With the powerplant mounted from one spoke, the mass distribution between spokes and the center of gravity of the spokes must be adjusted to provide for rotation about the station centerline. Generally, the mass of the spoke that supports the reactor must be decreased and the cg's of the two opposite spokes must be shifted outward. The cg shift required varies from 4 to 20 feet depending on the ratio of the spoke weights and the original mass distribution in the spokes. The mass adjustments can be accomplished without compromising the usefulness of the three-spokes.

The index to station stability, the ratio of the moment of inertia about the spin axis to that about an axis in the spin plane, is in the range of 1.55 to 1.70. With such a high moment ratio, the station will be inherently stable and will require minimum control.

2.8 INSTRUMENTATION AND CONTROL (III, SECTION 3.3)

The schematic conceptual design for the instrumentation and control system for the man-rated SNAP-8 system is shown in Figure 2.2-1.

The primary loop instrumentation consists of reactor start-up and control drum rotary position indicators; reactor inlet and outlet NaK flowmeters; reactor outlet NaK pressure gauges; pump differential pressure gauges; reactor and boiler outlet temperature thermocouples; reactor flux detectors, and temperature monitors within the primary loop. All logic is voted on a 2 out of 3 or a 3 out of 4 basis to minimize the probability of accidental shutdown.

The requirement for continuity of operation of the mercury and heat rejection loops is less stringent than that of the primary loop since parallel redundancy of loops is employed and, therefore, an intermediate step between alarm and scram is included; namely, the transfer of operation from a disabled loop to the remaining loop. In addition to the variables sensed in the primary loop, condenser mercury level and alternator output variables are measured.

The instrumentation of the NaK heat rejection loops is very similar to that of the other loops. The sensors are similar or identical to those of the primary loop in that NaK is the fluid medium rather than Hg; however, the technique of instrumentation and logic voting closely parallels that of the Hg loops.

Only flow and temperature are measured within the shield cooling loop, and even the flow indication may be removed possibly since flow measurement of the shield cooling loop can be inferred from existing parameter measurements within the primary loop. The secondary coolant-lube loops, however, must be instrumented in a manner similar to the primary and power conversion loops because of the motor and bearing coolant interfaces among these loops.

Data display includes the use of individual indicators for each sensor in critical portions of the instrumentation system even though this technique requires a greater quantity of amplifiers and indicators. Advantages are, however, that:

- The operator may directly compare all sensors at each measurement point at any time.
- Rapid human assessment of each situation is possible.
- Long term drift of a particular sensor channel may be determined from sequential data readings.
- The recording of data may be reduced to a single sensor channel at each location.
- Periodic testing of the instrumentation system permits the operator to confirm the calibration of both indicators and recorders.

A control system designed to follow load changes and introduce compensation into the power conversion loops as well as the reactor primary loop is shown in block diagram in Figure 2.8-1. The alternator electrical output controls the flow rate of its associated Hg loop by adjusting the motor speed of the Hg pump. In addition, the summed electrical output of the two alternators is used to control the reactor power output by adjusting the position of the reactor control reflector drums. Thus, changes in the electrical KVA demanded by the load are reflected in both the primary and power conversion loop operating conditions.

2.9 PLANT REPLACEMENT (II, SECTION 5.5 AND III, SECTION 3.1)

The modified SNAP-8 includes redundant components and will be subject to repair operations by the crew, and consequently is expected to exceed the design life of 10,000 hours. However, it cannot be expected that the powerplant will endure for 5 years and, therefore, the design provides for periodic replacement of the entire powerplant.

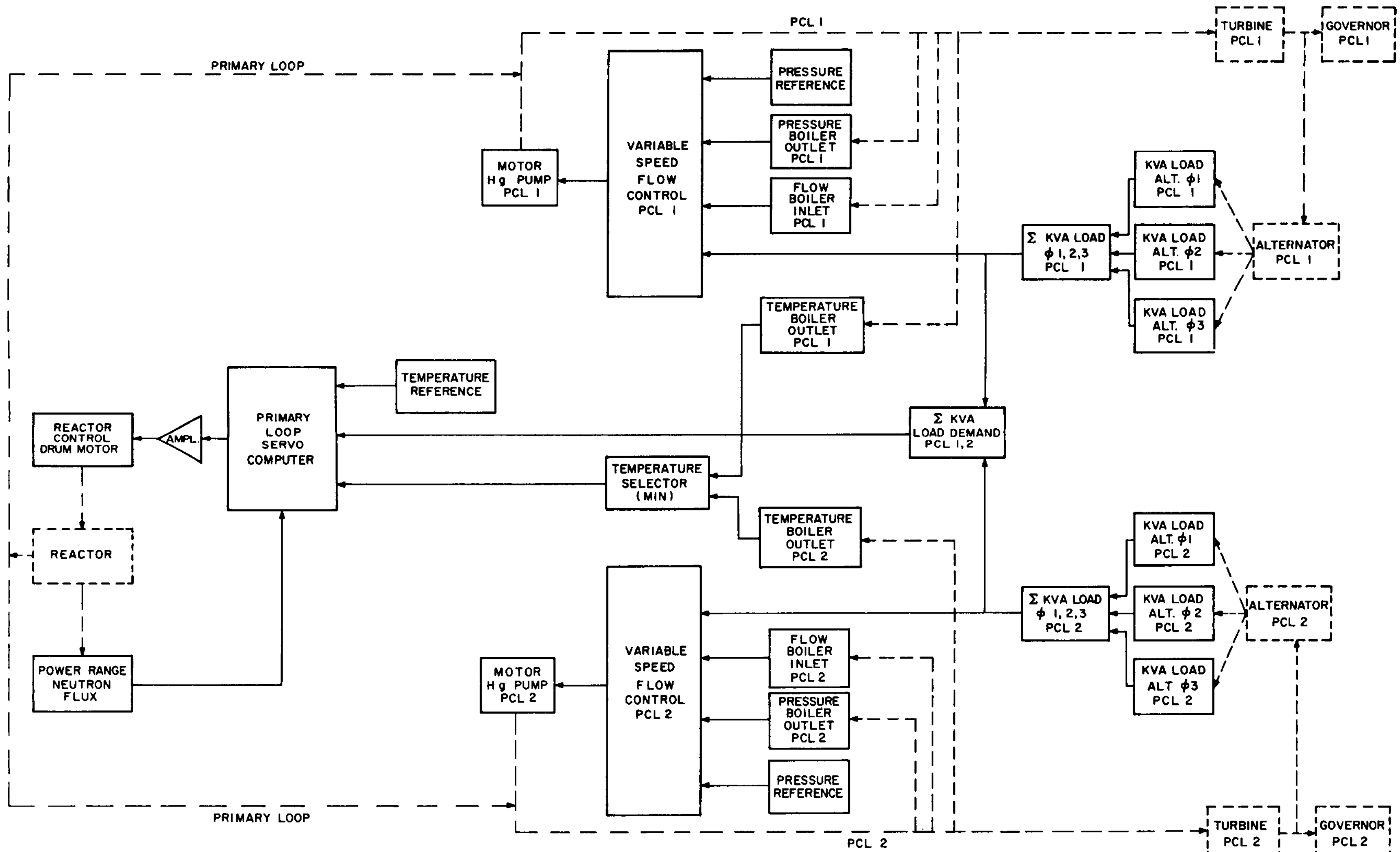


Figure 2.8-1. Control System Block Diagram

The replacement powerplant includes the reactor, primary loop components, power conversion equipment, primary radiator, and the replaceable portion of the shield as a completely assembled and checked unit. In the launch configuration shown in Figure 2.9-1, a disposal propulsion unit, secondary radiators, and approximately 21,000 pounds of station resupply stores are included. The complete replacement unit is 38.5 feet high and has a diameter of 21.7 feet to match the Saturn IB booster.

The propulsion unit is used for disposal of the old reactor during the replacement procedure. During launch it is mounted inside the primary radiator, suspended from the framework which supports the power conversion equipment. The primary radiator for the initial station is suspended from the hub of the space station at launch and is subject to tension loads, whereas, the replacement unit is mounted directly on the SIB booster at launch and is subject to compression loads. Added fin thickness and stiffening rings are necessary in order that the primary radiator be capable of sustaining launch loads without buckling.

The original secondary radiator launched with the space station can have a design life of five years and need not be replaced with the remainder of the powerplant. However, a replacement can be provided with little weight penalty by using the structure required to support station re-supply stores as a secondary radiator.

2.9.1 STORAGE IN ORBIT (III, SECTION 3.1)

Each replacement powerplant is brought into orbit about one year in advance of its planned use to serve as a spare for the operating unit. This eliminates the delays inherent in preparing a plant for launch in the event of premature failure of the currently operating plant. The total number of launches required is not increased.

The principal problem to be overcome in the "year-long" storage is the prevention of freeze-up of the radiators. The approach adopted is to provide a thermal shroud to reduce heat loss from the radiators during launch and storage in space. Prior to launch, the powerplant is heated from ground power. During storage, waste heat from the space station is used to maintain temperature and coolant is circulated by a pump.

The thermal shroud is a close fitting, rigid glass laminate over several layers of aluminized mylar. After rendezvous with the space station and separating from the

Figure 2.9-1. Launch Configuration of Replacement Plant

booster, the disposal propulsion unit is removed from inside the radiator using a logistics spacecraft. The powerplant is then mated to the hub of the space station. The secondary radiator interior is entered by station personnel to remove the resupply stores.

2.9.2 REPLACEMENT AND DISPOSAL TECHNIQUE (II, SECTION 5.5 and 5.6)

The powerplant is replaced by the series of actions illustrated in Figure 2.9-2. At Step 1, the power, control, and instrumentation cables that are the only lines crossing the station/powerplant interface are disconnected by a crew number within the sealed environment of the boom and radiator. At Step 3, the propulsion unit that is brought up with the replacement plant is used to boost the old reactor into a 400 year circular orbit. Three firings are used as illustrated in Table 2.9-1 and a total solid propellant weight of 540 pounds is required. Three firings are required to minimize the individual thrusts and, thereby, assure that no firing error will result in an uncontrolled entry of the reactor into the atmosphere. At Step 5, the new powerplant is moved from the hub storage position to an approximate position near the boom. At Step 6, the De Havilland Rods (II, Section 5.5.3) are used to pull the powerplant onto the boom. The powerplant compartment is resealed and the cables are reconnected. At Steps 7 and 8, powerplant start-up is initiated and the protective insulation is jettisoned.

The maximum dose received at the station as a result of the replacement was calculated as a function of the rate at which the old powerplant is accelerated away from the station. The dose is only 0.2 rem for acceleration rates as low as 0.01 ft/sec^2.

2.10 STATION BACK-UP POWER (II, SECTION 6.6)

In addition to the prime power requirements met by the nuclear system, highly reliable back-up power is required for pre-station activation, auxiliary, and "last-ditch" emergency power.

Station activation is expected to require 2 KWe for 50 hours. The power will be used to provide information via telemetry on the condition of the station before the first portion of the crew is launched into orbit. The power will also be used to assist in the rendezvous operation and will be used by the crew in the checkout and activation of the primary power source.

Auxiliary power will be required to meet the station power requirements when the prime power source is shut down for repair, maintenance, or replacement. The power level required is set at 14 KWe and the duration of the requirement is set at 5 days. The 14KWe power level is that level required to maintain the station on a normal basis exclusive of 21 KWe for experiments. The 5 day duration is set arbitrarily based upon considerations of the time required to shut down, repair, and re-start and the time required to replace the prime power source. One day is expected for this latter operation and, thus, 5 days provides a large safety margin.

The "last-ditch" emergency power of 4 KWe for 72 hours is required for possible deactivation of the station and for the escape of the entire crew. It will be the last power source available aboard the station.

A comparison of various power sources shows that H_2-O_2 fuel cells will provide the necessary back-up power to meet the requirements at minimum weight. Reliability, rather than weight, will be a more important consideration in the choice between power systems; however, definitive information for a reliability comparison is not presently available. The fuel cell weights necessary to meet each of the station demands individually are shown in Table 2.10-1. The total weight is not the sum of those shown, but rather the auxiliary plus the H_2, O_2 and tankage weight for pre-station activation and last ditch emergency for a total weight of 6087 pounds. This assumes that the pre-station activation and last ditch emergency power is generated with the fuel cells for auxiliary power. With modular design fuel cells, 4 KWe can be obtained from the 14 KWe rated cells even with gross failures.

2.11 SUMMARY OF POWERPLANT WEIGHTS

2.11.1 INITIAL POWERPLANT

The total weight for the initial powerplant is summarized in Table 2.11-1 for a 3-spoke station with the powerplant attached to one spoke. The shield weight is based upon a thermal power of 600 KWt although a power less than that will be required to produce 35 KWe net. The shield weight is, therefore, slightly greater than necessary. Weights are included for the support boom and deployment system for the powerplant. The radiators and the power conversion system are redundant consistent with the system shown in Figure 2.2-1. The weight for the back-up power sources consisting of H_2-O_2 fuel cells is also included.

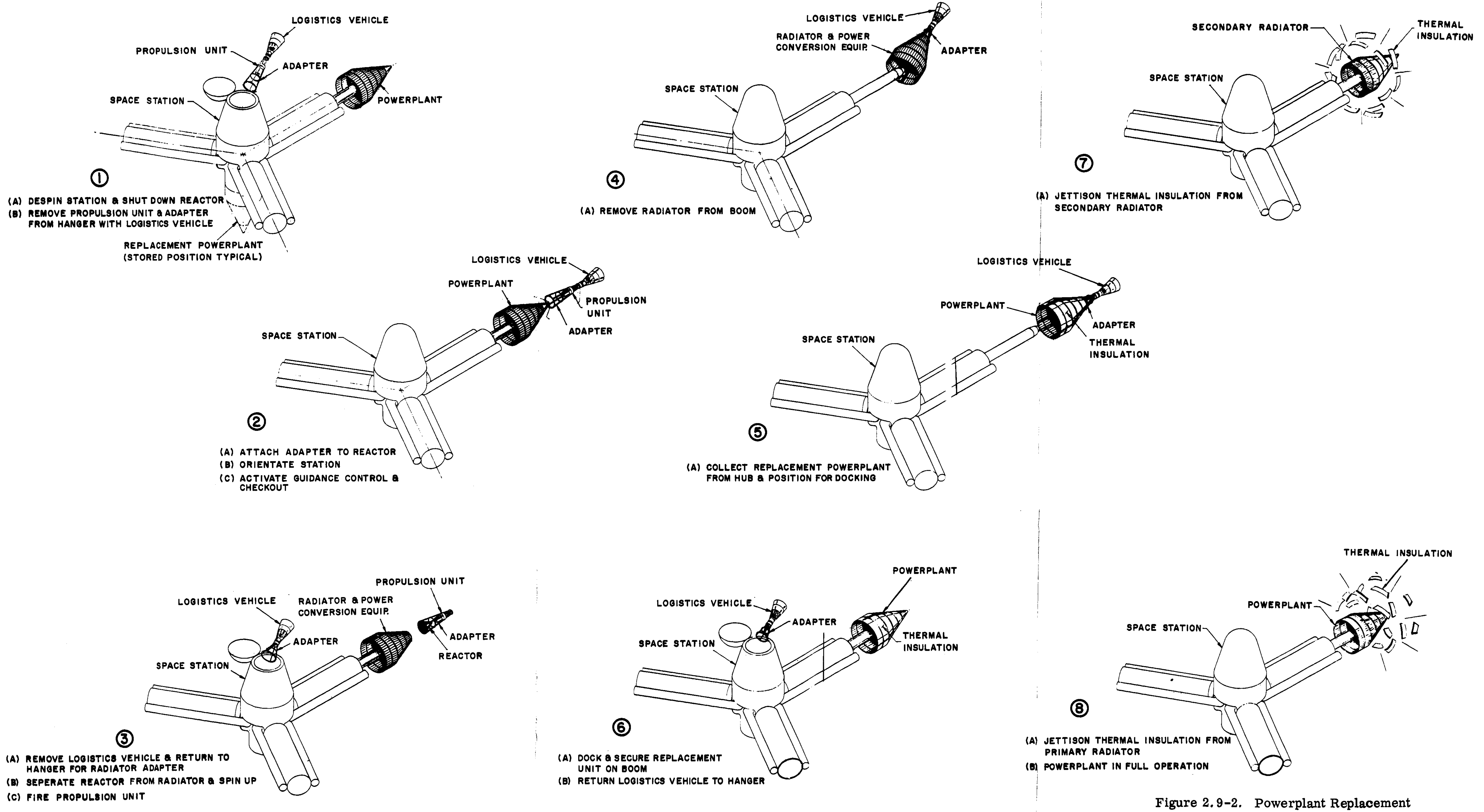
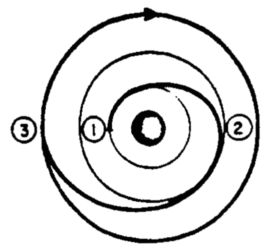


Figure 2.9-2. Powerplant Replacement Sequence

TABLE 2.9-1. ORBIT TRANSFER



INITIAL ORBIT	260 n. mi. ECCENTRICITY = 0
FINAL ORBIT	485 n. mi. ECCENTRICITY = 0
VELOCITY INCREMENT AT FIRST IMPULSE	224 fps
VELOCITY INCREMENT AT SECOND IMPULSE	363 fps
VELOCITY INCREMENT AT THIRD IMPULSE	143 fps
TOTAL IMPULSE	730 fps
PROPELLANT WEIGHT (Isp = 180 sec)	540 lb

TABLE 2.10-1. FUEL CELL WEIGHTS

	PRE-STATION ACTIVATION	AUXILIARY	LAST DITCH EMERGENCY
Power	2 KWe	14 KWe	4 KWe
Time	50 hrs	120 hrs	72 hrs
Fixed Weight	282 lbs	3380 lbs	965 lbs
Oxygen Weight	78 lbs	1320 lbs	225 lbs
Hydrogen Weight	9.75 lbs	164 lbs	28 lbs
Tankage Weight (supercritical storage)	75 lbs	650 lbs	157 lbs
Total Weight	445 lbs	5514 lbs	1375 lbs

TABLE 2.11-1. INITIAL POWERPLANT WEIGHT FOR 3-SPOKE SPACE STATION

SNAP-8 EGS INCLUDING REDUNDANCY

Reactor		540 lbs
Shield		
Permanent shield section	17,100 lbs	
Replaceable shield section	3,100	
	20,200 lbs	20,200
Shield Cooling System		100
Shield Support Structure		300
Primary Radiator (Redundant)		
Basic radiator matrix	2,085 lbs	
Header covers	440	
Header bumpers	100	
Feed armor	80	
Bulkhead	260	
Attachment rings	200	
Fasteners, etc. (10%)	340	
	3,505 lbs	3,500
Secondary Radiator (Redundant)		
Basic radiator matrix	1,120 lbs	
Header covers	200	
Edge members	120	
Stiffeners	60	
Feed armor	20	
Pig-tails	5	
Fasteners, etc. (10%)	153	
	1,678 lbs	1,700
Redundant Power Conversion System (PCS)		3,600
Support Structure for PCS		350
Boom Structure		1,800
Deployment System		500
Thermal Shroud (For plant shutdown)		120
Sub-Total for Nuclear System		32,710
Back-up Power (H_2-O_2 Fuel Cells)		6,090
Total Power System Weight		38,800 lbs

2.11.2 REPLACEMENT POWERPLANT

The total weight for the replacement powerplant is summarized in Table 2.11-2. Shield weight is reduced from 20,200 to 3,100 since only the replaceable shield section is necessary. The primary radiator weight is increased 200 pounds due to the additional stiffening necessary when the launch loads are in compression. Secondary radiator weight is reduced because the radiator structure also serves as support structure for the re-supply stores. The weight is shared evenly by the secondary radiator and the stores. Insulation to reduce thermal losses from the radiator during storage is provided. The disposal propulsion unit is also included since its weight reduces the payload capacity for re-supply stores.

TABLE 2.11-2. REPLACEMENT POWERPLANT WEIGHT FOR 3-SPOKE SPACE STATION

SNAP-8 EGS INCLUDING REDUNDANCY

Reactor	540 lbs	
Replaceable Shield Section	3,100	
Shield Cooling System	100	
Shield Support Structure	300	
Primary Radiator (Redundant)	3,700	
Secondary Radiator (Redundant)	940 (1)	
Redundant Power Conversion System (PCS)	3,600	
Support Structure for PCS	350	
Insulation (For storage)	580	
Thermal Shroud (For plant shut down)	120 (2)	
Total weight of replacement powerplant	13,330 lbs	13,330 lbs
Disposal Propulsion Unit	1,000 lbs	
Station Resupply Stores	21,330	
Resupply Section Structure	940 (1)	
Adapter Section	400	
	23,670 lbs	23,670
TOTAL LAUNCH WEIGHT		37,000 lbs

NOTES:

1. Secondary radiator also acts as structure for resupply section. 50% of weight is allocated to re-supply section structure and 50% to secondary radiator.
2. The cover for the thermal shroud housing is a structural element and is included with the adapter structure.

3. POWERPLANT SYSTEMS

This section summarizes the information obtained from the investigation of potential nuclear power sources and power conversion cycles. The application of a SNAP-8 mercury Rankine system and the inherent growth potential of this system was given particular attention.

3.1 POWER SOURCES (I, SECTION 4.1)

The electrical power range of interest has been taken on the basis of information supplied by NASA, as 4 to 6 KWe for a small station and 27 to 40 KWe for a large station. Accordingly, the nominal power ratings of the systems studied are 5 and 35 KWe. The only nuclear reactors that are reasonable candidates to meet these power requirements in the 1970 to 1975 time period are SNAP-2 for thermal powers up to 100 KWt and SNAP-8 up to 600 KWt. A radioisotope power source is a possible contender at the lower power level and an advanced high temperature reactor of undefined type is included to define the possible advantages of higher operating temperatures.

Emphasis is placed on using the SNAP-2 and SNAP-8 nuclear systems as developed with no or with minimum design modification. SNAP-2 and SNAP-8 Reactors have operated or are operating at present and the information obtained from the operation, control, and maintenance of these ground tests systems will be of significant value in adapting the systems for use with manned stations.

3.2 POWERPLANT CYCLES (I, SECTION 4.2)

Various combinations of the above thermal power sources with mercury-Rankine, steam-Rankine, thermoelectric and Brayton cycle power conversion systems have been considered as possible powerplants as listed in Table 3.2-1.

The comparative evaluations indicate the following:

- <u>5KWe SNAP-2 with Hg Rankine Power Conversion</u>

  Either a modified SNAP-2 or Sunflower type turbo-alternator package can be utilized to obtain 5 KWe. The SNAP-2 system flow rate will have to be increased 22 to 33% above the present design value to provide the necessary power. System weight will be approximately 1200 to 1300 pounds.*

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* Weights do not include shielding.

TABLE 3.2-1. CYCLE CONDITIONS FOR EVALUATED POWERPLANT SYSTEMS

POWER OUTPUT KWe	HEAT SOURCE	POWER CONVERSION CYCLE	CYCLE TEMPERATURE, PRESSURE *
5	SNAP-2 Reactor	Hg Rankine	1150 °F
		Steam Rankine	1000 to 1150 °F and 1000 to 1600 psia
		Thermoelectric	1100 °F
	Isotope	Neon Brayton	1500 °F
14 to 22	SNAP-8 Reactor	Thermoelectric	1100 °F
35	SNAP-8 Reactor	Hg Rankine	1100 to 1250 °F and 125 to 265 psia
		Steam Rankine	1100 to 1250 °F and 1000 to 1600 psia
		Neon Brayton	1200 °F
35	Advanced	Neon Brayton	1500 °F

* For dynamic systems, turbine inlet conditions are given. For the thermoelectric systems, average hot-junction temperature is given.

- 5KWe SNAP-2 with Steam-Rankine Power Conversion

  Radiator area requirements are excessive due to the low efficiencies and low radiator temperatures that can be expected with steam components in this power range. Additionally, the necessary components are not available and there is no experience with high efficiency steam components in such small sizes which further makes this cycle unattractive.

- 5KWe SNAP-2 with Thermoelectric Conversion

  A two-loop SNAP-2 power system with Lead-Telluride thermoelectric elements in a separate heat exchanger can produce a cycle efficiency of about 4.8%. The necessary 5KWe can thus be generated with a reactor thermal power slightly greater than 100 KWt. System weight will be about 1500 to 1700 pounds.*

- 5KWe Radioisotope with Brayton Cycle Power Conversion

  A one-loop, radioisotope Brayton cycle with a neon working fluid is a promising system with a 1500°F turbine inlet temperature. The lowest system weight among the dynamic systems considered can be obtained by this cycle; however, significant safety problems are involved in the use of the megacuries of radio-isotope required.

- SNAP-8 with Thermoelectric Conversion

  A two-loop system with lead-telluride thermoelectric elements in a separate heat exchanger and with a NaK heat rejection loop was investigated. Both EM and centrifugal pumps were used. The results show that an upper limit of 20 to 25 KWe exists at a limiting power of 600 KWt. System weights will be somewhat greater than the SNAP-8 Hg Rankine System; however, at power levels below 25 KW, the system warrants consideration because of its inherent high reliability, two single-phase loops, simplified start-up and control, and reduced reactor temperatures.

- 35KWe SNAP-8 with Hg Rankine Power Conversion

  This system was examined in detail and alternate cycles using the present SNAP-8 components were investigated. Results indicate that the major components can be readily adapted without modification in cycles that incorporate either operating or standby redundancy. System weight including redundant components will be 8500 to 9000 pounds.

- 35KWe SNAP-8 with Steam-Rankine Power Conversion

  Low radiator temperatures result in radiator areas about twice that of the Mercury Rankine Cycle and, correspondingly, greater system weight. High

* Weights do not include shielding.

turbine efficiencies are difficult to obtain because of the small turbine size, low volumetric flow rate, and relatively large losses due to manufacturing limitations. The cycle does not contain any inherent advantages that will warrant its development.

- 35KWe SNAP-8 with Brayton Cycle Power Conversion

  The SNAP-8 reactor is a poor match with Brayton cycle power conversion unless turbine and compressor efficiencies of 80 to 85% can be attained. Otherwise, the limiting reactor temperature of 1300°F results in low cycle efficiencies and large radiator areas. Also, reactor power may exceed 600 KWt. High efficiency components improve the attractiveness of the cycle; however, even with maximum improvement, radiator areas will be two to four times greater than those of the Rankine cycle at SNAP-8 temperatures.

- 35KWe High Temperature Reactor with Brayton Cycle Power Conversion

  A reactor that can provide a 1500°F turbine inlet temperature can achieve a cycle efficiency greater than 20% with a Brayton cycle that incorporates high efficiency components. Radiator areas approach those of the present SNAP-8 system.

3.3 SNAP-8 MERCURY RANKINE POWER SYSTEM (I, SECTION 4.2.1 AND II, SECTION 6.1)

The previous discussion of results showed that the SNAP-8 Reactor with some combination of a Mercury Rankine power conversion system is the only reasonable contender as a nuclear power source for a large space station in the early 1970's. Consequently, at NASA direction, major emphasis was placed on the adaptation of this system to the large 3-spoke station discussed in the conceptual design.

A principal aim was to determine if the SNAP-8 components as presently being developed can be used without redesign and modification to produce a man-rated system. Reliability is particularly important and can be increased by the proper inclusion of redundant components in the present SNAP-8 system. When operating, however, redundant components can modify the system operating characteristics. To determine that the components can be adequately matched to modified Hg Rankine cycles, the operating characteristics of the SNAP-8 components were defined, the characteristics were included in a computer program, and the program was used to determine a range of possible operating conditions for various modified cycles. The principal components that are of significance are:

- The reactor and its startup system
- The primary NaK pump/motor/assembly (PMA)

- The mercury jet/centrifugal PMA
- The heat rejection loop NaK PMA
- The NaK to mercury boiler
- The mercury to NaK condenser

Cycles that included redundant components in parallel and either two or three power conversion loops (PCL) in parallel were examined. The three PCL system results in a low cycle efficiency and a reactor power greater than 600 KWt. Additionally, the major reliability gain is attained with two loops.

The characteristics of the pumps are such that they may be operated in parallel within loops; however, the reliability studies indicate greater improvement for parallel PCL's.

Two PCL's were found to operate efficiently in parallel and to result in a decrease in reactor outlet temperature of 30 °F and a decrease in mercury boiling temperature of about 90 °F. Reactor power is increased somewhat but it is less than 600 KWt. The reduced boiling temperature enhances boiler reliability by an approximately 10 fold reduction in corrosion rate and the two PCL system improves system operational flexibility and the reliability for continued delivery of power. Typical operating conditions are given in Figures 2.2-2 and 2.2-3.

Station integration studies show a need to minimize radiator area and the primary radiator area was reduced from 1065 ft^2 to 950 ft^2 by the combined effects of a reduction in mercury subcooling from the design value of 143 °F to 100 °F and an increase in NaK heat Rejection Loop (HRL) flow rate from the design value of 36,700 pounds/hour to 54,000 pounds/hour. The greater flow rate can be obtained with the present pump and condenser by decreasing the resistance of the radiator feeds, headers, and tubes.

The results show that all of the SNAP-8 rotating components and the condenser can be adapted to modified cycles providing man-rated reliability without modification or redesign. The boiler will require re-configuration for ease of integration.

3.4 SNAP-8 GROWTH POTENTIAL (III, SECTION 4)

As in common with most nuclear dynamic systems, the SNAP-8 EGS incorporates significant design margin that can be used to provide power in excess of the 35KWe rating without increased weight. The amount of additional power that can be obtained depends upon the performance of the individual components and the cycle in which they are used. Evaluations of up-rating potential were made for the Reference SNAP-8 system shown in Figure 3.4-1 and the modified system shown in Figure 3.4-2. The component design characteristics were used in the evaluations.

The Reference SNAP-8 system with one power conversion system can attain a maximum power of about 48 KWe. The alternator is the first component to reach the limit of its capability and to restrict power to this level; however, other components similarly restrict power at slightly higher levels. Therefore, significant up-grading of practically all components is required for power levels above about 50 KWe.

The modified SNAP-8 system with parallel power conversion systems can attain a power level of 48 KWe with a 600 KWt reactor power. Higher electrical outputs at higher reactor powers are discussed in the Classified Appendix to Topical Report No. 3. The most serious limit on capability is that of radiator area. The SIB booster will be used to resupply the space station and the maximum fixed radiator area that can be included in the payload envelope is about 2020 ft^2. With part of the area allocated to the secondary coolant-lube radiators, a power limit of about 60 KWe is imposed. The components by constrast, are adequate to a power level approaching 80 KWe.

Comparison of the results obtained for the reference and modified SNAP-8 systems shows that both systems are apparently limited to 48 KWe. For the reference system, the limitation is imposed by alternator capability which is defined; however, in the modified system, the limitation is imposed by the 600 KWt design reactor power, with higher power levels not discussed here because of classification requirements. If greater reactor power is attainable, the limitation for the modified system could possibly be 60 KWe due to radiator area restrictions.

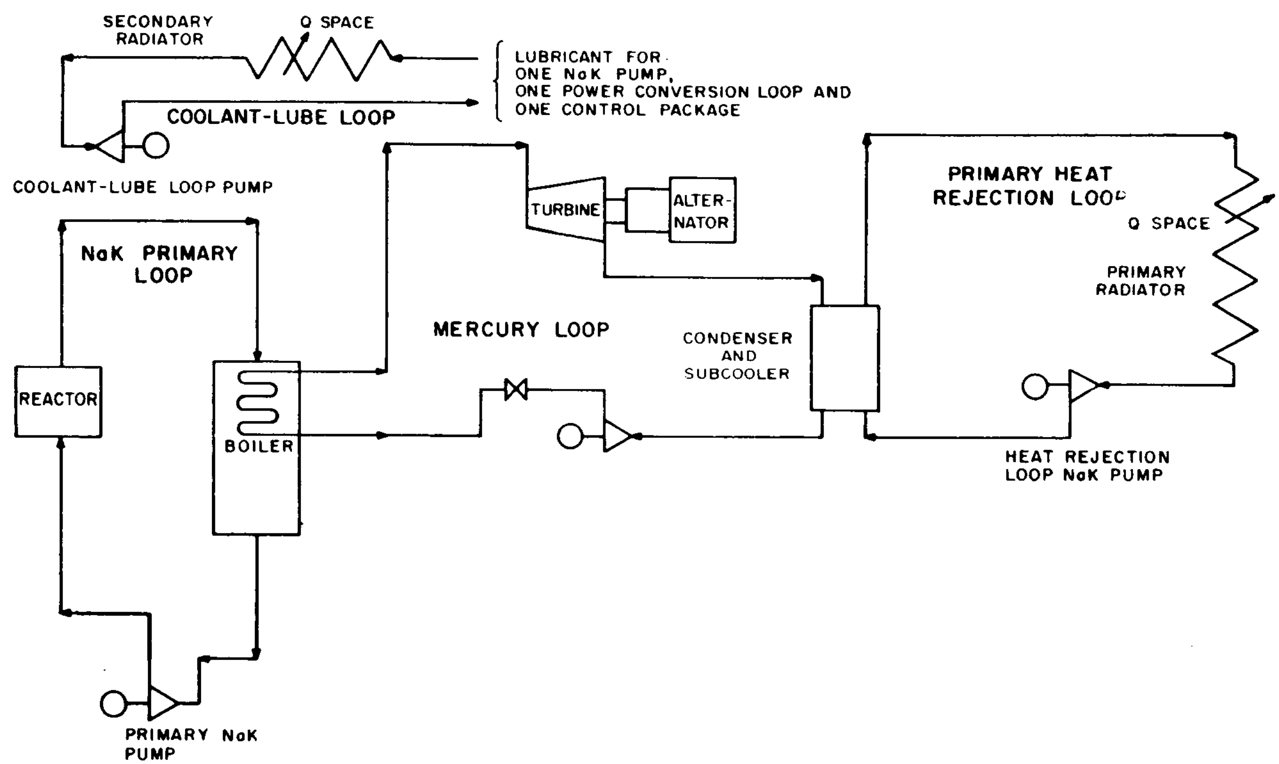


Figure 3.4-1. Reference SNAP-8 System

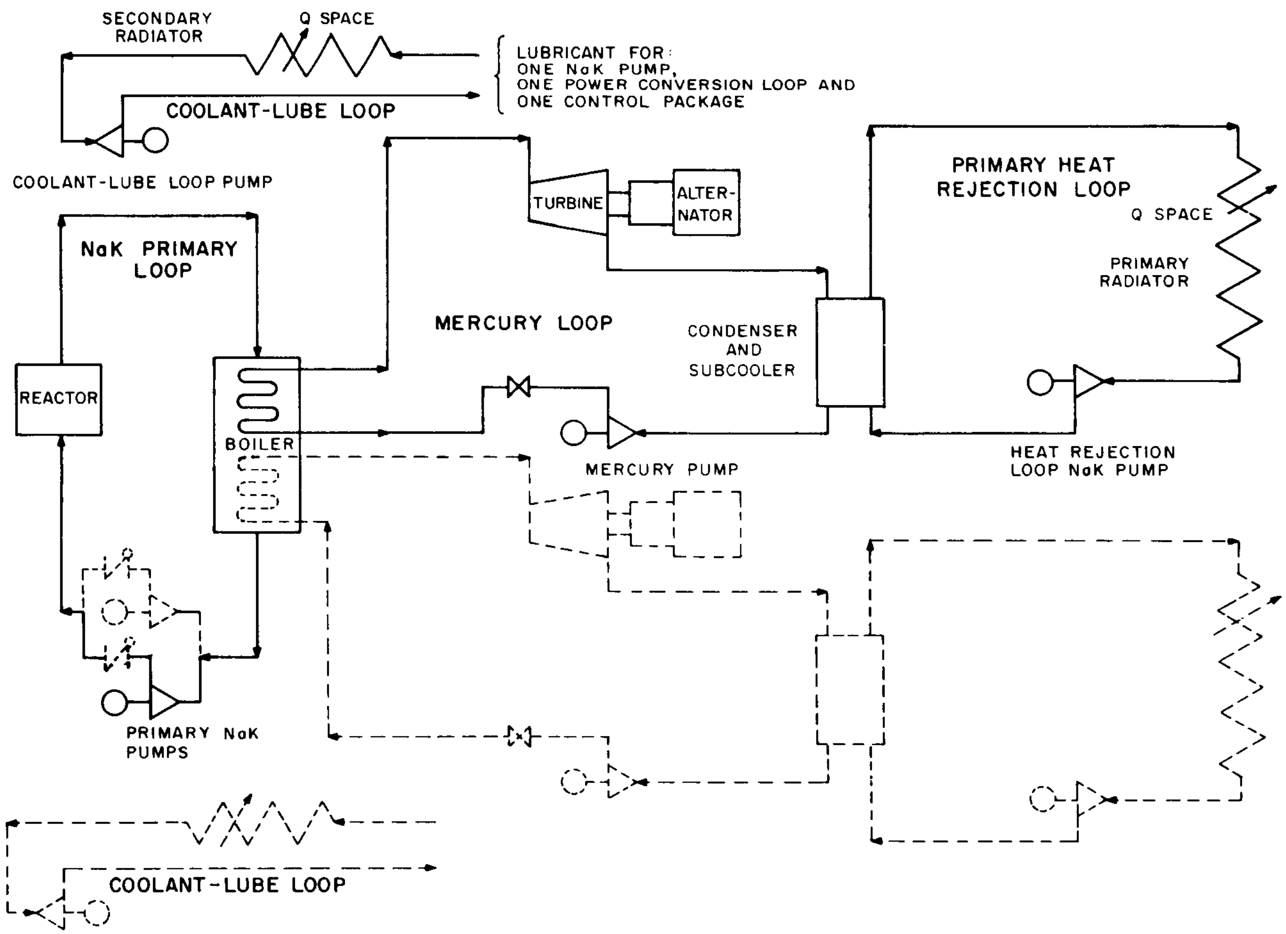


Figure 3.4-2. SNAP-8 with Redundant Components in Parallel Loops

4. OPERATIONAL FACTORS

This section summarizes the information obtained from the study of operational factors including nuclear system reliability, special instrumentation and controls for man-rating, manpower requirements, and restart capability.

4.1 RELIABILITY (II, SECTION 4)

The reliability of the modified SNAP-8 power system must be considered using both quantitative numerical reliability analysis and qualitative engineering judgement. This combined consideration is necessary because the system includes some elements that are not amenable to reliability analysis. This consideration is important because low weight or operational advantages are of no importance if the necessary reliability cannot be achieved.

The potential methods that can be used in modifying and adapting SNAP-8 for a manned mission are listed in Table 4.1-1. Combinations of these improvements can increase system reliability from the present goal of 0.9 for 10,000 hours to the 0.95 for 5 years defined for the space station. The results obtained in the study of each improvement are discussed as follows:

- Redundant Components within Loops

  Redundant components may be included within loops as illustrated in Figure 4.1-1. It is not practical with the present component design to include either a redundant reactor, boiler, or heat rejection loop in this arrangement because of the complexity of the valving and sensing systems that would result. The redundant rotating components that are included can result in a reliability gain provided that the added valves and the added sensing and control systems have a failure rate 1/10 to 1/100 that of the particular component. Otherwise, reliability can actually be decreased.

  With pumps in parallel, the greatest reliability increase is obtained if both pumps are operated simultaneously rather than singly.

- Redundant Loops

  Redundant components may be included in parallel loops as illustrated in Figure 3.4-2. This method has the advantages that additional valves are not required except with the primary NaK pump, each power conversion loop (PCL) is essentially identical to the basic SNAP-8 power conversion loop, fully redundant heat rejection loops are provided, and the PCL's may be operated singly or in parallel to produce the desired power. Valving, sensing, and control requirements are simplified relative to providing

TABLE 4.1-1. POTENTIAL RELIABILITY IMPROVEMENTS

- REDUNDANT COMPONENTS WITHIN LOOPS
- REDUNDANT LOOPS
- INSTRUMENTATION AND CONTROL SYSTEMS
- DAMAGE PREVENTION: PROTECTIVE SYSTEMS AND CREW ACTION
- LESS SEVERE OPERATING CONDITIONS
- COMPONENT REPLACEMENT AND MAINTENANCE
- REPLACEMENT OF ENTIRE POWERPLANT
- INTEGRATION WITH AUXILIARY POWER UNITS

redundancy discreetly within loops. System design can be such that loss of one PCL will not shutdown the other PCL and power can be continued to the station in the event of failure.

Generally, redundant components in parallel loops will result in a less complex powerplant with a greater reliability improvement than redundant components within the present loops.

- Instrumentation and Control Systems

The instrumentation and control system in the Reference SNAP-8 system is designed for minimum complexity as appropriate to an unmanned application. In adapting for the manned application, additional instrumentation and controls for operational flexibility to assist an operator in overcoming system faults is desirable.

- Damage Prevention by Protective Systems and Crew Action

Protective systems can be included in the powerplant to detect potentially damaging operating conditions, and either act to correct the particular conditions, or shut down the affected components before damage occurs. Protective systems will, thereby, increase the probability of attaining design life by increasing the protection provided to the components. Such systems can be included because the powerplant will include restart capability and therefore can survive an accidential shutdown and because the crew is available to diagnose the cause of the shutdown, make necessary connections, and initiate plant restart.

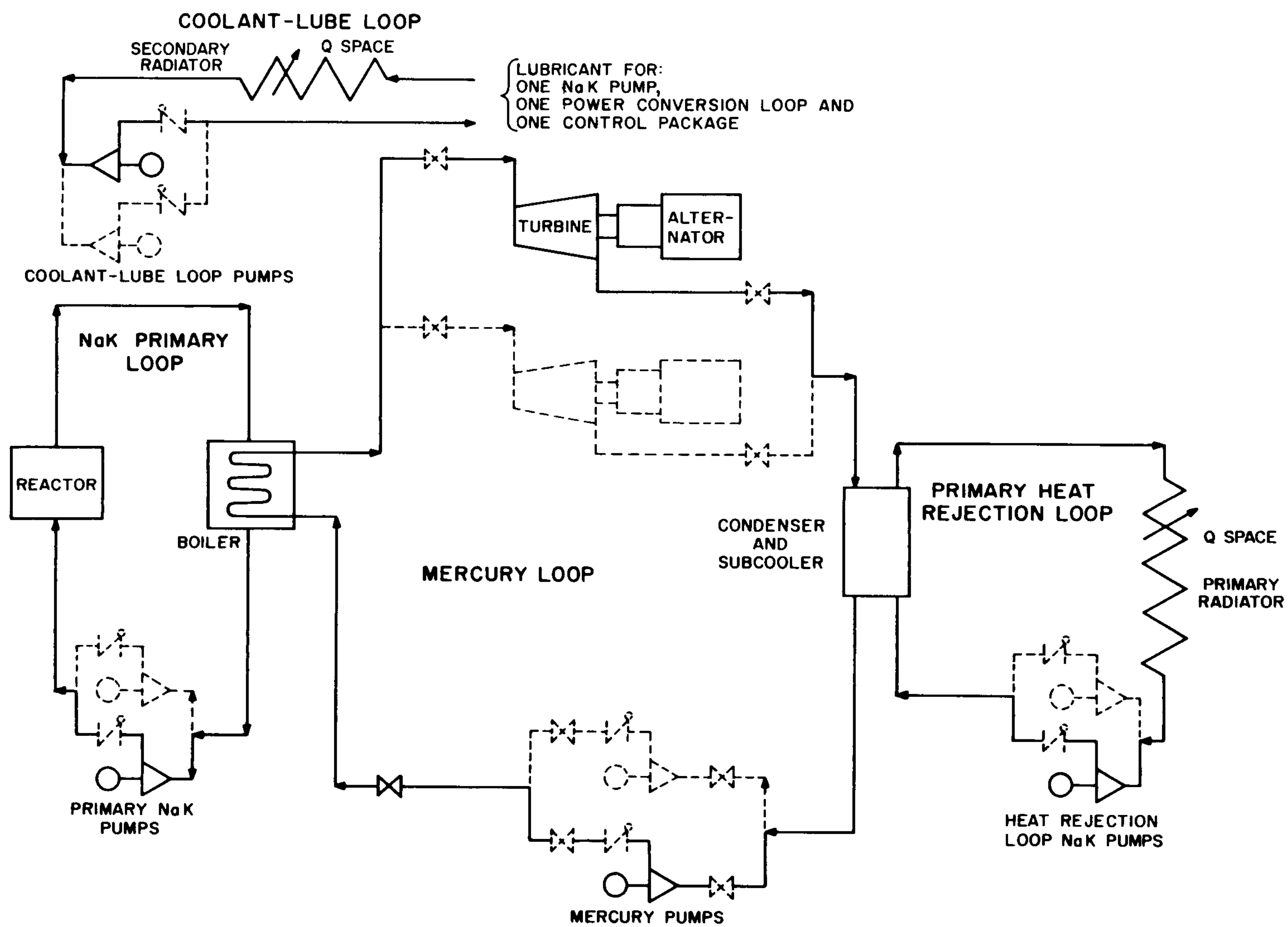


Figure 4.1-1. SNAP-8 With Redundant Components Within Loops

- Less Severe Operating Conditions

  Two methods of reducing the severity of the present SNAP-8 operating conditions were identified. The first is to operate two power conversion loops from one boiler: each mercury loop will be at reduced temperature and pressure. This reduces boiling temperature in the mercury boiler from about 1130 to 1050°F which is particularly significant, as it results in an approximately ten-fold reduction in boiler tube corrosion rate. The boiler is a sensitive component because it is near the limit of present material technology and a redundant boiler cannot be included practically.

  The second method is by providing a shield cooling system that can transfer the heat generated in the shield into the cycle and thereby reduce the reactor power requirements.

- Component Replacement and Maintenance

  The components of the nuclear power system can be divided into two broad categories:

  - Components that can be located remotely from the reactor and the power conversion loops.

  - Components that are a part of, or attached to the reactor and the conversion loops.

  The former category will include the bulk of the instrumentation, controls, and power conditioning equipment. Such equipment will be modular in design and will be included within the space station environment. Thus, this entire category of equipment can be made accessible for maintenance or replacement by proper plant arrangement.

  The latter category will include the loop components and the primary instrument sensors that will be connected directly to the loops. There is a significant amount of repair, adjustment, and replacement that can be accomplished on some of the loops, start-up mercury injection system, primary instrument sensors and the controls and protective systems provided that the powerplant components are enclosed in a sealed, accessible compartment. A system design has been developed that allows for unrestricted maintenance and repair, without incurring a weight penalty. The degree of diagnosis, repair, and replacement possible on these components will be limited only by the skills and capabilities of the crew and the tools and replacement parts available on the station.

- Replacement of Entire Powerplant

  The station design life is 5 years, whereas the design life of SNAP-8 for unmanned applications is slightly over one year. Consequently, the design provides for both plant refurbishment, and periodic powerplant replacement.

With replacement capability, the reliability for delivery of rated power is made approximately equal to the reliability of replacement, independent of the actual reliability of the powerplant. The reliability of the powerplant is then of primary importance in determining the probable number of times that replacement will be required.

To attain high replacement reliability, a simplified replacement technique for a ground assembled, thoroughly checked, and unitized powerplant is emphasized.

4.2 MANPOWER REQUIREMENTS (I, SECTION 3.5.1)

An analysis of the operating manpower requirements for a nuclear powerplant based on a SNAP-8 type system with one reactor and two sets of turbomachinery and auxiliary equipment was made.

All reactor power plants operating today use at least two operators continuously to observe reactor power, temperature, and pressure on a continuous basis and to make visual inspections of the conversion system and auxiliary reactor systems at frequent intervals. The SNAP-8 system as presently developed will ideally require no operator attention for its design life; however, in adapting it for use with a manned station and in increasing reliability, additional instrumentation, controls and diagnostics will be added to the system. Diagnostics are especially important in locating and correcting system faults to allow a return to operation.

A periodic review of the instrumentation readout to check on system performance will be necessary as there are often indications of impending failures that can be detected and prevented. Also, operator attention at start-up, shut-down, and at any testing is desirable to allow operator "over-ride" at malfunction of the automatic systems. Additional operator attention will be required for periodic visual plant inspections and for preventive maintenance.

With a highly automated plant designed for minimum attention and upkeep, it is estimated that manpower requirements, exclusive of unscheduled maintenance, will be about 3 man-hours/day. The individual breakdown of man-hours is given in Table 4.2-1; however, it is emphasized that the estimates are necessarily speculative and suitable only for planning until firmer values are provided by actual plant tests and qualification programs.

TABLE 4.2-1. NORMAL OPERATIONAL MANPOWER REQUIREMENTS

OPERATION	MANPOWER REQUIREMENTS
Normal Operator Attention	2 Man-Hour/Day
Review of Logs and Routine Diagnostics	1 Man-Hour/Day
Periodic Instrument Checks	3 Man-Hour/Month
Periodic Routine Instrument Maintenance	3 Man-Hour/Month
Visual Inspection Outside Station	5 Man-Hour/3 Months

4.3 INSTRUMENTATION AND CONTROL (III, SECTION 3.3)

A variety of measurements are required throughout the SNAP-8 powerplant loops in order to satisfy the monitoring and control functions, including:

- Temperature
- Pressure
- Differential Pressure
- Flow
- Rotational Displacement
- Reactor Flux
- Liquid Level
- Electrical Line Frequency
- Voltage
- KVA

The quantity of identical sensors at each measurement point must be established in accordance with protective system criteria. The criteria used here are:

- The protective system must sense and prevent all potentially hazardous situations; therefore, those parameters which reflect higher order hazard conditions must be instrumented and controlled with higher order redundancy.
- The powerplant system must rarely, if ever, shut down due to non-hazardous anomalies, such as a single channel instrumentation failure.
- An alarm indication must be initiated for every out-of-tolerance condition in the system.

- A majority of the sensors at each measurement point must indicate abnormal powerplant operation to cause either transfer of loop operations to a parallel loop or shutdown of the entire powerplant.
- A periodic, manual testing sequence must be rigorously followed to ensure proper instrumentation, control and protective system operation.
- Manual standardization of all equipment may be required to reduce the complexity of the instrumentation and eliminate the necessity of automatic self-checking hardware.
- For all critical parameters of the powerplant system, separate indicators for each sensor are provided to permit rapid diagnosis of any alarm condition and also provide greater operator confidence in each measurement.

An assessment is provided for:

1. Instrumentation of the primary loop; each power conversion loop, each heat rejection loop; each secondary cooling loop, and the shield cooling loop.
2. Automatic control of the powerplant:
   a. To follow the load under normal operating conditions.
   b. To effect the necessary change-over in case of failure of any portion of the powerplant to assure the continued operation of the powerplant.
3. A protective system for the entire powerplant to prevent hazardous situations from endangering either personnel or the space craft.

The results indicate that instrumentation can be provided with the proper logic to increase system reliability and flexibility without appreciably increasing the likelihood of accidental shutdown. Instrumentation of the proper type is generally available in stock, prototype, or development stages; however, adaption and qualification to SNAP-8 launch and operation conditions will be required.

4.4 RESTART CAPABILITY (III, SECTION 3.2)

There are at least three design areas of principal importance that will determine feasibility of shutdown and restart. These are:

- Providing for multiple mercury injections to the Mercury loop,
- Preventing the freeze-up of the heat rejection loops and the primary NaK loop and,
- Providing for positive reactor shutdown without rejection of the reflector.

4.4.1 MERCURY INJECTION SYSTEM

The present mercury injection system (Figure 4.4-1) operates only oncc and does not include any provision for restart; however, by relatively simple modification, the injection system can be modified to provide unlimited restart capability.

The mercury and oil tanks must be oversized to allow the injection of two mercury charges, only one of which is injected for the initial start. The modified system will then operate as follows:

- With the mercury liquid and vapor in the loop piping, the restart is initiated by the injection of the second charge of mercury.
- The mercury liquid and vapor are pushed ahead of the newly injected mercury, the liquid is partially or completely vaporized in the boiler, and passes through the turbine to the condenser.
- The excess mercury in the loop collects in the condenser and the mercury pump is started at the proper time.
- The injection of the second charge of mercury is completed or stopped.

At the end of start-up, the mercury loop will contain excess mercury that will partially flood the condenser reducing its effective condensing area. The mercury may be removed by including a bypass line as shown dotted in Figure 4.4-1. The mercury pump outlet pressure is greater than the injection pressure and therefore can be used to return the excess mercury to the mercury tank via the inventory control valve. The gas will be re-compressed for the next start-up.

4.4.2 SYSTEM FREEZING

At system shutdown, the heat rejection loops will continue to reject heat to space and will rapidly cool to the freezing point if they are not protected. Allowing the radiators to freeze and then using "defrosting" techniques for re-start involves undesirable technical problems and it appears that the loops must be kept fluid.

Minimum pumping temperatures (including safety margin) are about 175°F for the ET-378 used in the coolant-lube loops and about 150°F for the eutectic NaK in the cycle heat rejection loops. The radiators will reject about 43 KW total at these temperatures which is greater than can be supplied by station waste heat or reactor decay heat. Therefore, a thermal shroud will be required over the radiators during shutdown.

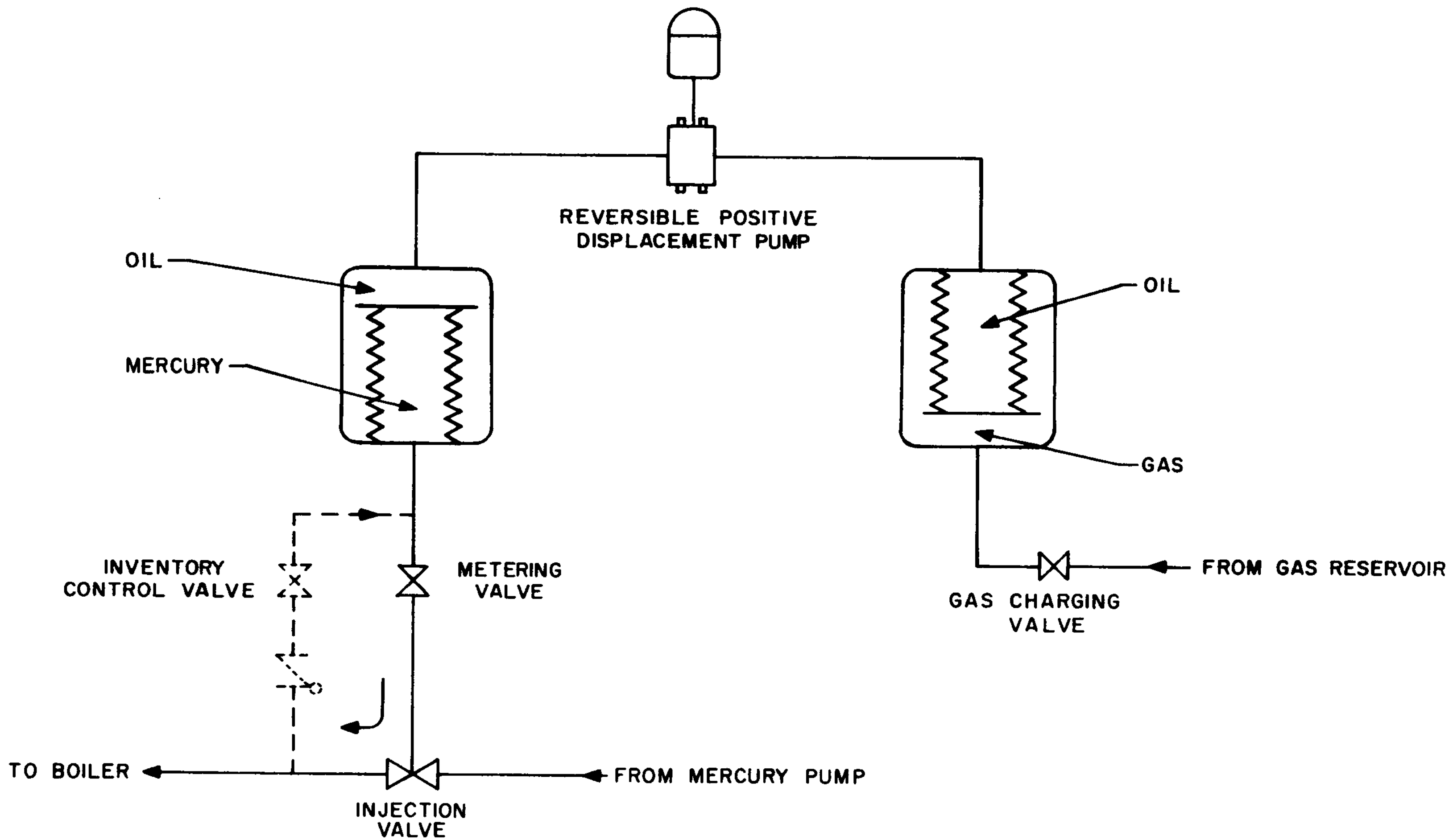


Figure 4.4-1. Mercury Injection System

A promising design is a disposable, aluminized mylar shroud that can be stored in a very small space as shown in View "C" of Figure 2.9-1. The release pins are explosively actuated to allow the first shroud to deploy. Rotation of the space station and the inertia of the ring segments causes the shroud to extend and maintain tension. When the powerplant is restarted, the shroud is released by burning through with an imbedded heater wire. The second and subsequent shrouds are then available for use. This sequence of operations is illustrated in Figure 4.4-2.

The radiator cooling rates are such that at least 6 and 30 minutes will be available, for deployment of the shrouds before the coolant-lube and NaK radiators, respectively, reach the minimum pumping temperatures.

The thermal shroud reduces the heat rejection capability sufficiently that only 7 KW is required to prevent freezing. More than 13 KW of waste heat are available from the $H_2 - 0_2$ fuel cells that will supply station power during plant outages and from reactor decay heat.

Flow at a low rate must be maintained in one of each of the two sets of heat rejection loops in order to distribute the heat to the system and to prevent the formation of frozen lines. Flow can be provided by the loop pump at reduced speed, a small pump in parallel with the loop, pump, or by a small EM pump (NaK loops only). The power requirements are not an important factor as flow will be only 1/20 to 1/5 of rated.

4.4.3 REACTOR SHUTDOWN MECHANISM

The present reactor is shutdown by an explosive release of the reflector and modification will be required in order to attain restart capability. The experience obtained in designing and operating the ground prototype reactor is available and the control and scram mechanism developed for the ground prototype reactor can be adapted to allow control, scram and restart.

Some redesign is desirable for simplification, lightening, and for positive drum lockout at final shutdown; however, the redesign will be simplified by the experience obtained in designing, manufacturing, and operating the test drive.

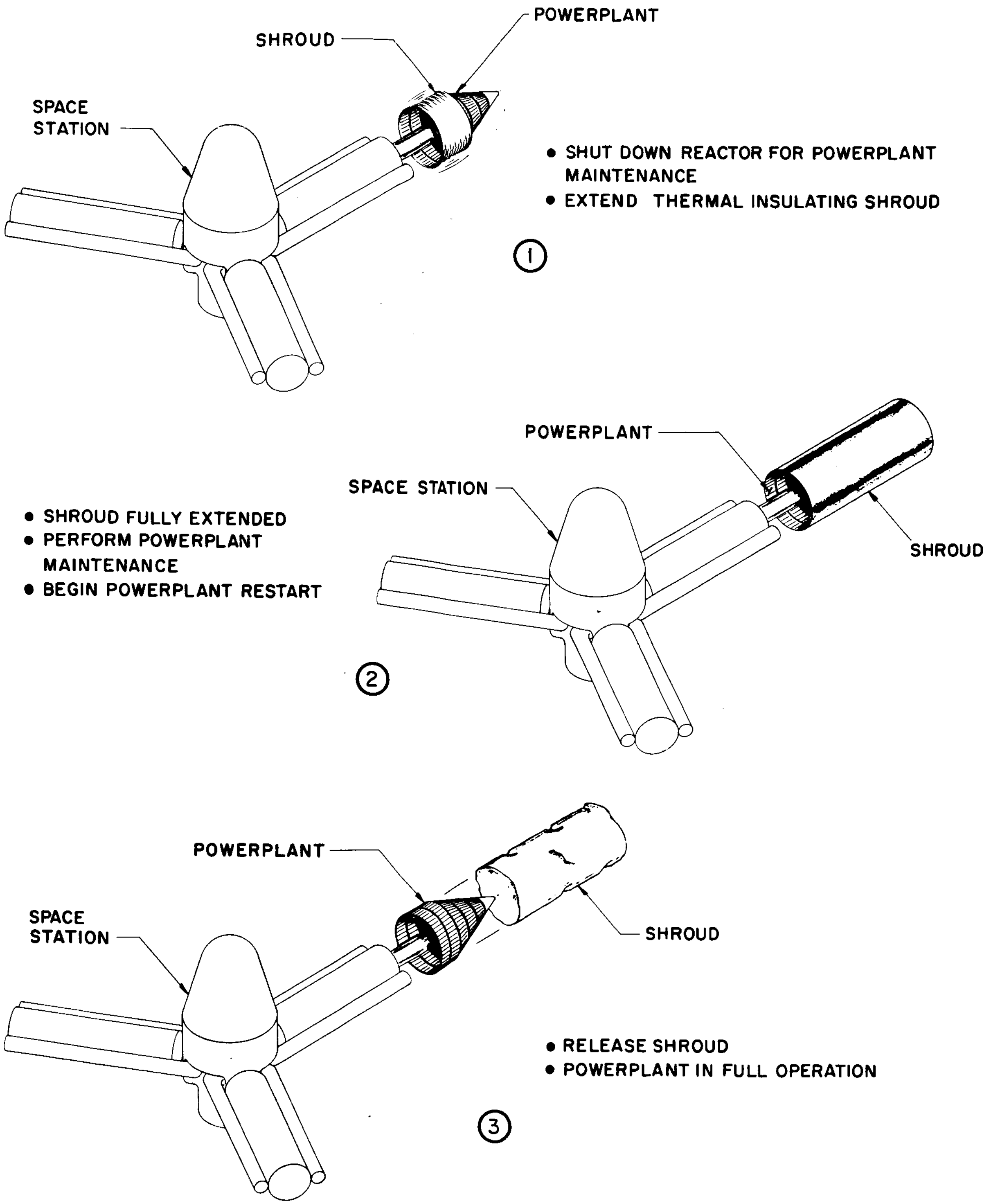


Figure 4.4-2. Disposable Mylar Thermal Shroud for Radiator

5. NUCLEAR HAZARDS

Evaluation of the nuclear hazards associated with a space station power supply, using a SNAP-8 reactor, indicates that no new or unique hazards will be introduced into the overall aerospace nuclear program. The degree of the potential hazards to populated areas is comparable to or less than that of other programs, including central-station power and marine propulsion.

To a certain extent, a man adds to the safety and reliability at launch, in that, positive lockouts can be left in the reactor to be removed manually after the proper orbit is attained. Also, a man can give greater assurance of positive shut down at the end of life and greater assurance of safe reactor disposal.

5.1 LAUNCH HAZARDS (I, Section 5)

The hazards at launch result primarily from the possibility of an accidental criticality either while the reactor is on the missile at the pad or as a result of an unsuccessful launch resulting in the reactor being immersed in hydrogenous material, such as the ocean. Without defining the mechanism for occurence, it was assumed that accidental criticality resulting in energy release of 100 megawatt seconds could occur either at the launch site or in off-shore waters. An excursion of 100 megawatt seconds is a conservative value since studies on SNAP reactors indicate that the upper limit for a power excursion probably does not exceed 80 megawatt seconds and may not exceed 50 megawatt seconds. This excursion is small compared to those studied for launches of nuclear powered missiles at both the Atlantic and Pacific Missile Ranges.

A release model which includes 100 percent of the noble gases and halogens was used. Release of other radio active isotopes is neglected except in the case where the reactor is assumed to undergo a destructive excursion under water. Fission product inventories at the time of the launch accident are calculated for two specific cases: the first with no previous reactor operating history, and the second in which the reactor has been operated for a period of acceptance testing, terminated thirty days prior to the launch.

Persons beyond 100 feet from the reactor will receive less than a lethal dose (400 R) from the prompt radiation of the excursion and persons beyond 300 feet will receive less than the "emergency dose" (25 r). With the excursion in the nose of the missile, any persons within 300 feet would be at least partially shielded by the missile structure or by the control buildings, launch building or other structures of the facility and these doses will be further reduced. If the excursion results from the missile abort into water, even greater reduction of dose will result from the shielding effect of the water.

Residual radiation resulting from the reactor excursion will decay rapidly. If the reactor has undergone acceptance testing a residual fission product inventory will result in a relatively long-lived radiation field of approximately 15 r/hr at 10 feet from the reactor and 150 mr/hr at 100 feet, unshielded.

The dose resulting from airborne radioactivity downwind from the launch accident is never a significant hazard. Inhalation of radioiodine results in a dose to the thyroid of less than 1 rad at 3 miles downwind. Whole body dose from the passing cloud is less than 0.1 rad at the same distance. Deposition of radioiodine may be sufficient to initiate milk control measures.

5.2 REACTOR RE-ENTRY HAZARDS (I, Section 5)

Regardless of the method chosen for disposal, re-entry must be considered - either because it is intended or because it can occur as a result of an accident.

Unless complete ablation in the upper atmosphere occurs, two major problems arise from the re-entry of the reactor at the end of power operation. If the reactor returns intact, and the core hydrogen is not released, a nuclear excursion must be considered likely as the probability of impact in water is approximately seventy percent. If the reactor is not intact but ablation is not complete, the fragments of the reactor will be highly radioactive unless the orbital lifetime has been long enough to allow decay of substantially all of the fission product inventory.

If the reactor re-enters at times less than 60 days after shutdown, the fission product inventory will dominate and there will be no significant increase in the direct radiation dosage as a result of an excursion. At a distance of ten feet from a fuel element, this fission product burden will not result in a lethal dose (400 R) during a 24-hour period. At distances greater than 40 feet, the "emergency dose" of 25 R will not be exceeded in the same period. For re-entry at times greater than 60 days the excursion dose can contribute to the total; however, the total dose is always less than the dose received at a 60 day re-entry.

Fission products can be released if the reactor impacts the surface. The worst case considered is re-entry 60 days after shutdown, accompanied by a 100 MW-sec excursion and release of fission products to the atmosphere at ground level.

The direct results of the excursion will be essentially the same as those discussed in the launch accidents. Reactor inventory (fission products retained in the core) will have no significant effect on the whole body dose from passage of radioactive cloud nor, of course, on the prompt dose from the excursion. The inventory will however, contribute to the residual radiation after an excursion. The cloud dose and the inhalation dose resulting from the release of excursion fission products and the residue of approximately 90 curies of Iodine-131 from power operations sixty days after reactor shutdown will result in radioiodine concentrations of 2.7 $\mu c/m^2$ at 10 kilometers under adverse radiological conditions. This concentration will be reduced to approximately 0.08 $\mu c/m^2$ at a distance of 100 kilometers downwind. These concentrations can result in iodine contamination of milk with corresponding thyroid doses, at the closer distance, of approximately five rad for an adult and fifty rad to an infant.

6. STATION/POWERPLANT INTEGRATION

This section summarizes the information obtained from the integration studies in the areas of shielding, station dynamics, auxiliary power sources, power conditioning, reactor replacement and disposal, and station electric propulsion.

6.1 SHIELDING (I, SECTION 3.2 AND II, SECTION 5.7)

Weights for lithium hydride/tungsten shields were predicted for the five space station configurations listed below.

- Cylindrical stations with 15, 20 and 33 foot diameters,
- A three spoke station with the plant attached to one spoke, and
- A three spoke station with the plant attached to the hub.

The weight analyses use as parameters;

- The separation distance between the reactor and the station,
- The closest approach distance of the rendezvous craft to the reactor, and
- The deceleration rate of the rendezvous craft.

The parameters cover a wide range including that of practical design interest. The shield is made up of three major components whose individual weights are determined by the particular parameters chosen and whose weights may be summed to obtain total shield weight. The shield components are:

- <u>The Station Shadow Shield</u> which provides protection to the crew inside the station,
- <u>The Rendezvous Shield</u> which limits the radiation exposure of the ferry crew during rendezvous or return operations.
- <u>The Scatter Shield</u> which provides additional neutron and gamma attenuation between the reactor and the station to reduce the dosage at the station resulting from neutrons and gammas scattered from the rendezvous shield.

These sections are not physically distinct but can be used for calculational purposes.

The weights are based on limiting the total radiation dosage to the crew to 22 rem during a 1 year tour of duty. This will consist of 16 rem inside the station, 4 rem during extra station operations and 1 rem at each rendezvous. The radiation source is a SNAP-8 Reactor at 600 KWt.

The shield design provides for a shield in two sections: one section that is permanently attached to the station and one section that is attached to the reactor. The permanent shield comprises approximately 85% of the total shield weight and a significant weight saving is obtained since only 15% of the shield is replaced with the powerplant.

In addition to the parametric analyses, a more detailed analysis and design was performed for a shield mounted from one spoke of the 3-spoke station. The examination was made to allow a comparison between weights predicted by parametric and detailed analysis, and thus, define the degree of optimism or pessimism contained in the parametric results. The comparison shows close agreement between the analyses with differences not exceeding about 20% in the practical range of interest.

Systems studies indicate that the heat generated in the 4 π shield can be removed by a NaK coolant loop and transferred to the subcooled mercury entering the boiler. A flow rate of about 1800 pounds/hour that can be provided from a bypass stream from the present primary NaK PMA or by a separate loop will be required. Maximum shield temperatures will occur in the actively cooled portion of the shield and will not exceed 1000°F. The passively cooled shield section will conduct heat to the shield surface to be radiated to space and maximum temperature will be about 450°F.

The shield can account for 40% to 80% of the weight of a nuclear power system and, consequently, it is a large weight contribution where significant savings can be made by proper optimization. This study, as ground rules, has used the station configurations defined and has emphasized designs that result in minimum perturbation of station operations, to the detriment of the power system. In fact, however, in integrating a station and a powerplant there will be compromises on both sides to produce the optimum final station. These compromises are expected to reduce shield weight; especially the choice of station configuration, which can modify shield weight by a factor of 2 or 3.

Advantage has not been taken for the savings that can result from shield weight and material optimizations, reduced crew stay-time, partial shielding by station equipment and structure, or reduced dose due to occupancy at low dose rate areas.

6.2 STATION DYNAMICS (I, SECTION 3.4 AND II, SECTION 5.1)

The stability and balance of the three-spoke rotating station with a powerplant attached to either the hub or to one spoke was examined.

6.2.1 STATION BALANCE - SPOKE MOUNTED POWERPLANT

The component parts of the rotating station must be so arranged that the center of gravity of the station coincides with the geometrical center of the hub. A nuclear powerplant attached to the end of one spoke represents a concentrated mass which must be properly balanced by other components. The weight of the plant is a function of separation distance between the reactor and the station, and combining the data on the plant weight with that on station weight and its distribution, the allowable mass distribution within the station can be defined. The analyses show that the center of gravity of the two spokes opposite to the reactor must be shifted outward a distance of 4 to 30 feet depending upon the reactor/station separation distance, and initial station mass distribution. Total powerplant weights for typical parameters range from 24,000 to 36,000 pounds.

6.2.2 STATION STABILITY - HUB MOUNTED POWERPLANT

If the powerplant is attached to the central hub, then a concentrated mass is located on the spin axis. In this position it tends to increase the moment of inertia about the axes perpendicular to the spin axis, thereby decreasing stability.

Station stability may be attained by making the moment of inertia about the spin axis, I_z, either significantly larger or smaller than that about the mutually perpendicular axis I_x and I_y. The ratio, C, of I_z to I_x and I_y, is thus an indicator of the degree of stability.

Station designers currently favor a ratio greater than 1.0 as this results in an inherently stable station (somewhat like a gyro) that requires a simpler stability control system.

A ratio less than 1.0 can also result in a stable station (somewhat like the stability of a spinning artillery shell), but the control system is more complex. A ratio greater than 1.0 can be attained with a hub-mounted powerplant; however, the allowable separation distance between the reactor and station is a strong function of the mass distribution in the station spokes. Since separation distance is directly related to shield weight, there is also a significant effect on plant weight. These effects are shown in Figure 6.2-1 where the station moment of inertia ratio is plotted versus separation distance for three different distributions of mass in the spokes, namely:

- Parabolic with mass increasing toward the station centerline,
- Uniform over the length of the spoke, and
- Parabolic with mass increasing away from the station centerline.

If a minimum ratio of 1.1 is taken as a criterion, the allowable separation distances and the corresponding plant weights are:

Mass Distribution	Distance, ft Separation	Powerplant Weight, lbs
• Parabolic to ℄	25	46,000
• Uniform	53	38,000
• Parabolic From ℄	75	32,000

At the initiation of this study, space station studies indicated that a parabolic mass distribution with mass increasing toward the station centerline best approximated the spoke weight distribution. As shown above, this leads to excessive plant weights due to the large amount of shielding required at close separation distances. This is also the basis of the mid-term conclusion that hub-mounted powerplants will result in significantly higher weights than spoke-mounted powerplants.

However, continuing station studies now indicate that the spoke mass-distribution is more nearly uniform or actually increasing away from the station centerline. In this case, lower plant weights, equivalent to those of spoke-mounted powerplants, can be obtained and hub mounting will be the favored position. Hub mounting has inherent advantages in initial deployment, in plant replacement, and it allows an equal distribution of mass between the spokes.

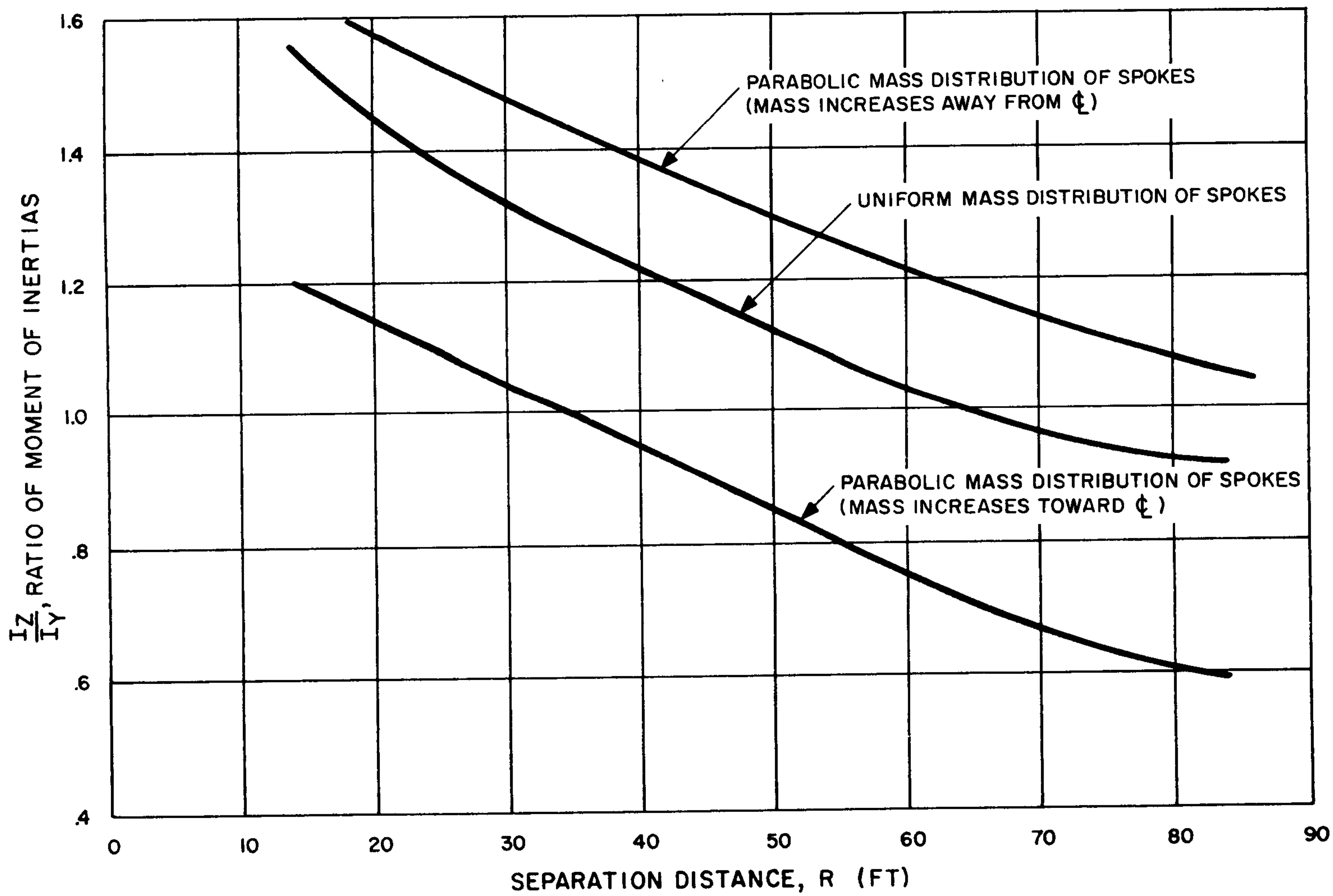


Figure 6.2-1. Mass Moment of Inertia Ratio $\frac{Iz}{Iy}$ vs. Reactor Separation Distance for a Hub Mounted Powerplant

There is also a possibility that a control system can be designed that will allow the station to be stably controlled with a moment ratio less than 1.0. In such a case, lower powerplant weights at higher separation distances can again be obtained with hub mounted powerplants.

There is not sufficient information available at the present time to make a final determination on the mounting position for the powerplant on the 3-spoke station. The hub mounted position is favored provided that the spoke mass distribution is such as to allow separation distances in the order of 70 feet and greater or control system will allow a moment of inertia ratio less than 1.0.

6.3 STATION BACK-UP POWER (II, SECTION 3.3 AND 6.6)

Back up power for the large 3-spoke station was considered for pre-station activation power, for auxiliary power when the main powerplant is inoperative for replacement, for "last-ditch" emergency escape power, and for emergency back-up, to the auxiliary power. Because of the high level of reliability that will be required, consideration was given only to those power sources that have the potential of achieving ultra-high reliability in the 1968 to 1972 time period. These include solar photo-voltaic, fuel cells, batteries, and chemical auxiliary power units.

A comparison on a weight basis indicates that the auxiliary power requirements of the station can best be met by H_2-O_2 fuel cells. The power requirements and the weights for the various systems are summarized in Table 6.3-1.

TABLE 6.3-1. COMPARISON OF BACK-UP POWER SOURCES

		Pre-Station Activation	Auxiliary	Emergency Back-Up	"Last-Ditch" Emergency
Auxiliary Power Requirements	Power Level, KWe	2	14	7	4
	Time, hrs.	50	120	360	72
	Total Power, KWe-hrs	100	1680	2520	288
Silver-Zinc Batteries	Weight, lbs	1100	18700	28000	3200
Solar Photo-Voltaic	Weight, lbs	2200	15400	7700	4400
Chemical APU	Weight, lbs	540	7700	10460	1430
H_2-O_2 Fuel Cell	Weight, lbs	445	5514	4931	1375

The emergency back-up power was included as back-up to the emergency power but it is judged unnecessary as plant replacement is expected to require 1 day and the auxiliary power provides for 5 days. This is an adequate safety margin.

6.4 POWER CONDITIONING AND DISTRIBUTION (II, SECTION 6.5)

The power conditioning components will convert the 120/208 V-3 phase, 400 cycles output of the SNAP-8 turboalternators to the form required by the loads. Generally, these loads will operate at 28 volts dc or 120 volts ac with the approximate division of loads given below:

- (35%) 120 volts ac, 400 cps ± 1%
- (40%) 28 volts dc, ± 2%
- (25%) 30 to 40 volts D.C. - unregulated

The power conditioning system will receive power from single or parallel SNAP-8 turboalternators at part or at full load and from the emergency or auxiliary power supplies.

Special purpose equipment such as specialized communication equipment can require very high voltages and/or very close regulation and such equipment will have special power conditioning equipment designed as part of its subsystem.

Power will be transmitted as generated as 3 phase ac. The transmission and distribution systems will supply the various load equipment as well as protect the other power conditioning, loads, and generator from faults.

With a single turbo-alternator, the present SNAP-8 system for current, frequency, and voltage control can be utilized. Provision for use of a spare generator in case of systems failure can also be made if temporary power is supplied by secondary batteries via an inverter-diverter for very short periods until the auxiliary power supply can be activated.

With operation of parallel SNAP-8 turbo-alternators from one reactor, the control, and transmission and distribution system will require modification. A flow control will be required for each turbine to permit operation at reduced powers and temperatures and to match output to load demand. The turbine speed can be controlled by flow control adjustments regulated by frequency sensing. In case one of the turbo-electric systems is out of service, the control system can automatically increase the output of the remaining unit to permit one turbogenerator to provide full power.

Power distribution for parallel turbo-alternators can be provided by parallel busses, each supplying a discrete set of isolated loads. Contactors at each load can open upon load faults and permit the generator to continue to supply the other unfaulted loads. Double-throw contactors with mechanical interlocks will allow the safe transfer of loads from one bus to another at operator discretion.

6.5 REACTOR STORAGE, REPLACEMENT, AND DISPOSAL (II, SECTION 5.5 AND 5.6 AND III, SECTION 3.1)

The replacement nuclear powerplant for the 3-spoke station will include the reactor, primary loop components, power conversion equipment, radiators, and replaceable shield section as a completely assembled and checked unit. A propulsion unit to be used for disposal of the old reactor will be brought into orbit with the replacement plant.

The replacement powerplant may be stored as a spare aboard the station for about one year and the NaK loops must be kept fluid during this period. The alternate exists of filling the radiator loops only when ready to start-up; however this does not appear attractive considering the problems of handling NaK in space and the problems of preheating the radiator structure prior to the injection of the fluid. With the loops filled and circulating at reduced rate, heat losses can be reduced by a thermal shroud to less than 2 KW which can be provided from station waste heat. The present pumps can be operated at reduced speed and without external lubrication to provide circulation or small EM pumps can be provided.

The replacement and disposal technique for a spoke mounted powerplant is discussed in Section 2.9.2 and pictured in Figure 2.9.2. A similar technique is also adaptable to a powerplant mounted from the hub of the station. This latter mounting position has the additional advantage that replacement may be accomplished without de-spinning the station.

Reactor disposal is by transfer to a 400-year orbit to allow decay of fission products to acceptable levels before re-entry. Only the reactor, including replaceable shield section and primary loop components, but excluding the power conversion system and radiators, is disposed of in this manner in order to reduce propulsion requirements and increase the W/C_DA of the disposal package.

Three methods of transfer are compared in Table 6.5-1. Method 1 requires three separate firings of the propulsion unit, the first firing is limited to 224 ft/sec in order to meet the criterion that a 180° guidance error causing the velocity increment to be applied in the opposite direction must not result in an orbit lifetime of less than 60 days. The second and third firings provide the velocity increments for transfer and circularizing to an orbit at 485 n. m. Methods 2 and 3 provide for disposal with the simplification of only two firings; however, the lifetime criterion for guidance error is not met. The latter two methods may be considered if positive assurance of direction can be confirmed prior to firing the propulsion unit. A fourth method (not shown) would be to use a single firing and transfer the reactor to an elliptic orbit. This has the disadvantages that greater propellant weights are required, the reactor will return to the space station orbit periodically, and the guidance error criterion will not be met.

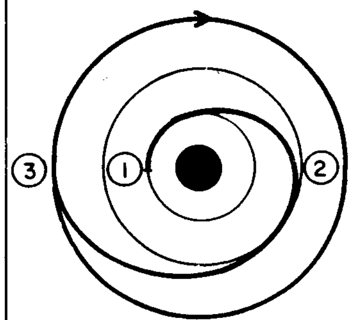
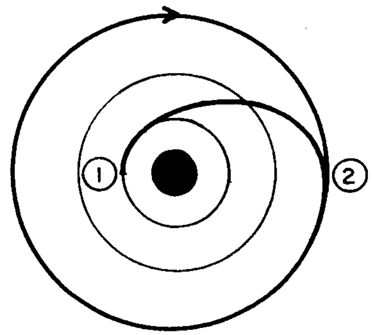
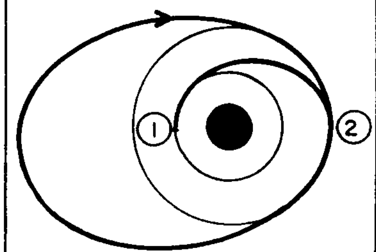
Three separate rocket motors are used for the three impulses. For high reliability, solid propellant with spin stabilization to maintain the correct thrust direction is used. Spin-up of the reactor is accomplished after release from the station and before the first impulse rocket is fired.

6.6 ELECTRIC PROPULSION (II, SECTION 7.2)

With excess electrical capability available as from a nuclear powerplant, a review of the space station design will show tasks that can be accomplished with electrical energy at large weight savings. An example is electric propulsion.

The large 3-spoke station presently requires about 16,000 pounds of chemical fuel per year for attitude control, spin maintenance, and orbit maintenance. If electric propulsion is substituted for chemical propulsion, and the total impulse requirement is held constant the same task can be accomplished with 4400 pounds of mono-propellant for a fuel saving of 11,6000 pounds per year. If in fact, a nuclear source of low drag is used to provide station power, station drag and the impulse requirement is reduced and the fuel savings is even greater. This gain is partially offset by the increase in the nuclear power system weight of 1600 pounds to produce the additional power for electric propulsion, but the net effect is to reduce resupply requirements by 10,000 pounds per year. With an SIB re-supply cost of 1000 dollars/pound minimum, a program savings of \$10,000,000/year is obtained.

TABLE 6.5-1. ORBIT TRANSFER METHODS

Method	1	2	3
			
Initial Orbit	260 N.M. Eccentricity = 0	260 N.M. Eccentricity = 0	260 N.M. Eccentricity = 0
Final Orbit	485 N.M. Eccentricity = 0	485 N.M. Eccentricity = 0	394 N.M. Perigee Eccentricity = .03
Velocity Increment at First Impulse	224 fps	367 fps	224 fps
Velocity Increment at Second Impulse	363 fps	353 fps	591 fps
Velocity Increment at Third Impulse	143 fps		
Total Impulse	730 fps	720 fps	815 fps
Guidance Error Criteria Met	Yes	For Second Impulse Only	For First Impulse Only
Propellant Weight (I_{sp} = 180 sec)	540 lb	530 lb	600 lb

7. SNAP-8/SOLAR PHOTO-VOLTAIC POWER SYSTEMS COMPARISON

Solar photo-voltaic and SNAP-8 electric power systems were compared for the three-spoke station at a power level of 40 KWe. Two solar photo-voltaic systems; one described by the study performed by Lockheed Aircraft Corporation for the station and the second described by an independent study reported in the Third Topical Report were included. The information on SNAP-8 as modified and adapted for a manned application was taken from the I, II and III Topicals of this study. The SNAP-8 systems use chemical and electrical propulsion for station-keeping.

The SNAP-8 system that uses electrical propulsion for station keeping must produce 47.5 KWe to provide 40 KWe net to the station. The additional 7.5 KW of power is used to charge a set of batteries that are discharged at a 27.5 KWe rate to provide power for a pulsed, monopropellant propulsion system. A pulsed arc-jet can reduce station fuel requirements by a factor of 3.5 to 4 and thereby reduce the yearly logistics requirements.

The initial launch weights for the systems are given in Table 7.1-1. As shown, the power system weights for the solar photo-voltaic systems are lower than those of SNAP-8 however, when the higher station fuel requirements for the solar systems are included, the initial launch weights are essentially equivalent. The fuel requirements for the solar photo-voltaic systems are higher due to solar array drag and special orientation requirements.

The yearly re-supply requirements for the systems are given in Table 7.1-2. As shown, the re-supply weights for the SNAP-8 systems are lower in both cases and, particularly so, with the inclusion of electric propulsion. Minimization of re-supply is important because the smaller re-supply vehicle (e.g. Saturn I-B) has a high cost ($1000/pound minimum) compared to the initial vehicle (Saturn V at $250/pound). The cumulative booster costs attributable to the power systems are summed in Figure 7.1-1. Initial launch costs vary over a range of only $2,000,000. SNAP-8 with electric propulsion results in minimum cost at 1 year and a cost advantage of $32,000,000 at 5 years. Without electric propulsion, SNAP-8 results in equal cost at 1 year and a cost advantage of $7,000,000 at 5 years. Estimates of launch costs vary widely and these costs at 250 and 1000 $/pound are minimal. Costs four times as great are also estimated, in which case, the cost advantage of $32,000,000 would be increased to $120,000,000.

TABLE 7.1-1. INITIAL LAUNCH WEIGHT OF SOLAR CELL AND NUCLEAR SYSTEMS
40 KWe

	Solar Photo-Voltaic		Man Rated SNAP-8 **	
	Power System Study (Lockheed)	Power System Study (GE)	Without Electric Propulsion	With* Electric Propulsion
Power System, lbs	22,150	29,950	39,180	40,910
Fuel (one year), lbs	15,275	16,635	7,985	2,250
Support Structure and Tankage for fuel, lbs	2,110	2,300	1,100	230
Total	39,535 lbs	48,985 lbs	48,265 lbs	43,390 lbs

** Includes 6087 pounds H_2 - O_2 Fuel cell as auxiliary power

* Must generate 47.5 KWe to provide 7.5 KW for electric propulsion

TABLE 7.1-2. YEARLY RE-SUPPLY REQUIREMENTS FOR SOLAR PHOTO-VOLTAIC AND NUCLEAR SYSTEMS
40 KWe

	Solar Photo-Voltaic		Man Rated SNAP-8	
	Power System Study (Lockheed)	Power System Study (GE)	Without Electric Propulsion	With Electric Propulsion
Power System, lbs	6,790	6,930	13,000	14,700
Fuel (one year), lbs	15,275	16,635	7,985	2,250
Support Structure and Tankage for fuel, lbs	2,110	2,300	1,100	230
Total	24,175 lbs	25,865 lbs	22,085 lbs	17,180 lbs

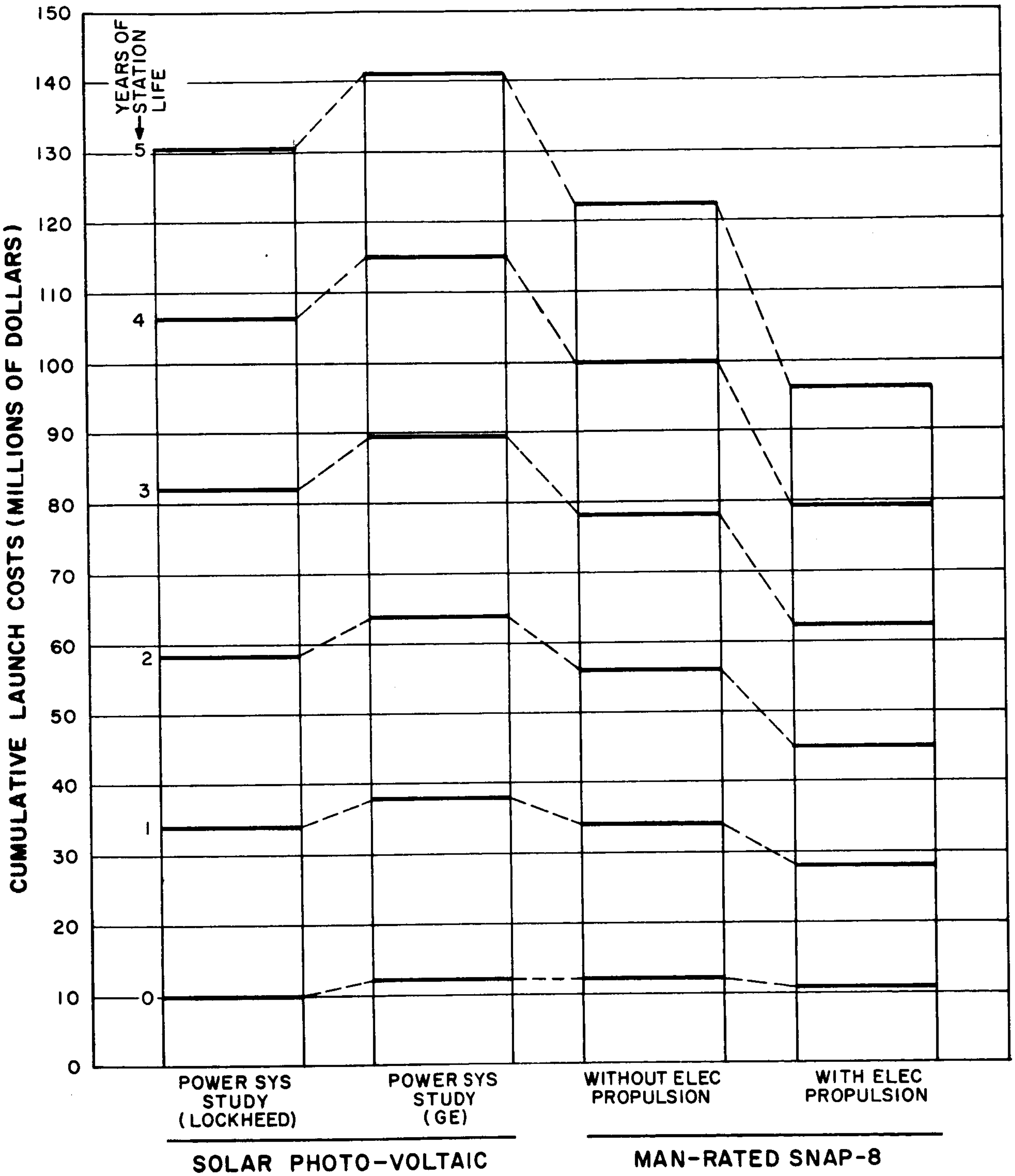


Figure 7.1-1. Cumulative Launch Costs, Millions of Dollars

Only a gross assessment of system cost is possible. The solar photo-voltaic systems will require at least one ground test and one flight test; however, the system is modular and a 1/6 section will provide the necessary test data. The cost of a full size 40 KWe system without development is estimated at $40,000,000. Considering the necessary spares, the cost necessary to produce the first flight system is given in Table 7.1-3 as $160,000,000.

The cost for man-rating SNAP-8, including necessary ground test systems is estimated at $80,000,000. Production systems, after development, will be in the range of $5,000,000 each; however a cost of $10,000,000 each is estimated for the first two flight test systems. Total costs to the first system are $160,000,000.

The comparison shows that:

- When all weights attributable to a power system are included, initial launch weights for solar photo-voltaic and SNAP-8 power systems are approximately equivalent.
- The yearly station resupply requirements for a SNAP-8 system can be about 7000 pounds lower than those of the solar photo-voltaic system, resulting in a saving of $32,000,000 over a station life of 5 years.
- The total cost required to provide the first flight qualified system of both types is about equal.

If, in fact, there is to be more than one station, then the nuclear system with its significantly lower cost per system will result in a large program savings.

TABLE 7.1-3. ESTIMATED TOTAL COSTS TO FIRST FLIGHT SYSTEM

Solar Photo-Voltaic	$ (10^6)	Man-Rated SNAP-8	$ (10^6)
Ground System Test of 1/6 Array	10	Man-Rating and Ground Tests	80
Flight Test of 1/6 Array		Flight Test of Full System	
Hardware (2)	20	Hardware (2)	20
Booster (2)	50	Booster (2)	50
Spare System	40	Spare System	5
First System	40	First System	5
	$160.0		$160.0

8. SNAP-8 DEVELOPMENT PROGRAM RECOMMENDATIONS

Phases II and III of this study concentrated on adapting the present SNAP-8 Mercury-Rankine system to provide a man-rated system. Emphasis was placed on using SNAP-8 components without modifications, or at least with a minimum of modification. This section summarizes recommendations for the next steps in producing a man-rated SNAP-8 system and recommendations that principally affect the design of SNAP-8. The technical recommendations are not of a type that will prevent the development of the powerplant if unexecuted. Rather, they are of a type that will result in a more optimum system with gains in reliability and flexibility. The gains must be balanced against the additional development time and costs.

The technical recommendations include discussion of:

- Improvements in shield calculational techniques and consideration of alternate shield materials,
- Reductions in reactor envelope to reduce shield weight,
- Re-arrangement of the NaK heat rejection loop components to allow continued operation with a condenser tube leak,
- A test to determine the feasibility of using one heat rejection loop to "defrost" a parallel loop.
- The use of alternate fluids with lower pumping points in the heat rejection loops to alleviate the problem of radiator freezing during shutdown.
- A back-up mercury boiler design, and
- Steps required to prove maintenance and repair techniques.

The program recommendations include discussion of:

- The need for a development program for a man-rated SNAP-8 system,
- The requirement for ground test systems,
- A conceptual design for a flight test configuration of a test system,
- Powerplant designs that are applicable for more than one mission, and
- Investigations of stability limitations on rotating stations.